Light Sterile Neutrinos: Evidence and Prospects

Fermilab Academic Lectures:

The Allure of Ultra-Sensitive Experiments

30 January 2013

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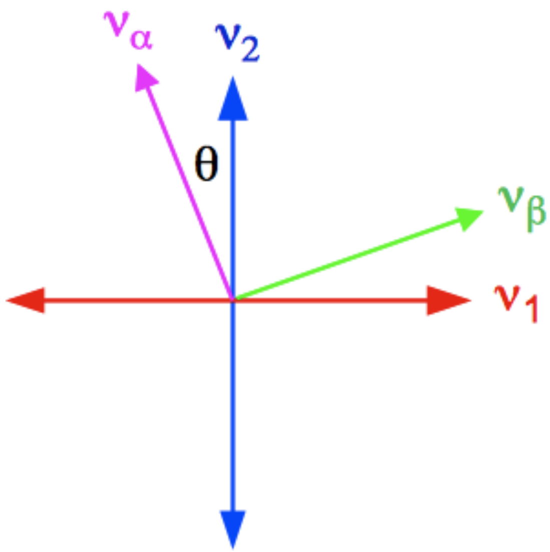
Outline

- Three Neutrino Mixing
- Experimental Hints For Beyond Three Neutrino Mixing
  - The LSND Result (“LSND Anomaly”)
  - Reactor Neutrinos at very Short-Baseline (“Reactor Anomaly”)
  - GALLEX and SAGE Calibration Data (“Gallium Anomaly”)
  - The MiniBooNE Neutrino and Antineutrino Data
- Prospects for Addressing These Hints
  - Complimentary approaches to address this challenging question are needed
  - We’ll review <u>examples</u> of different approaches being pursued

Simplified Neutrino Oscillations



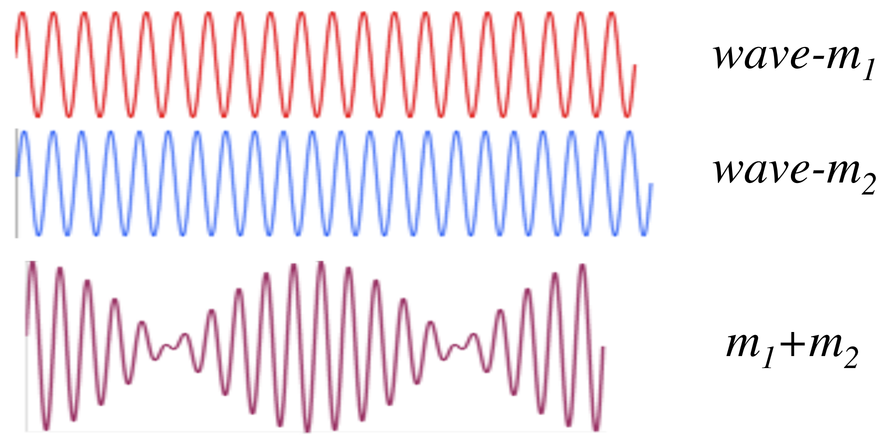
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m_{ij}^2 \frac{L}{E}\right)$$

The mixing angle, θ, determines the amplitude of the oscillation

Δm^2 determines the shape of the oscillation as a function of L (or E)

$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$



Three Neutrino Mixing

- Three neutrino mixing firmly established…

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

neutrino mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric & Long-baseline accelerator neutrinos

Quasi 2-neutrino mixing

Solar & Long-baseline reactor neutrinos

$L/E = 500\ \mathrm{km/GeV}$

$L/E = 15,000\ \mathrm{km/GeV}$

Three Neutrino Mixing

- Three neutrino mixing firmly established…

$$\theta_{12} \approx 34^\circ$$

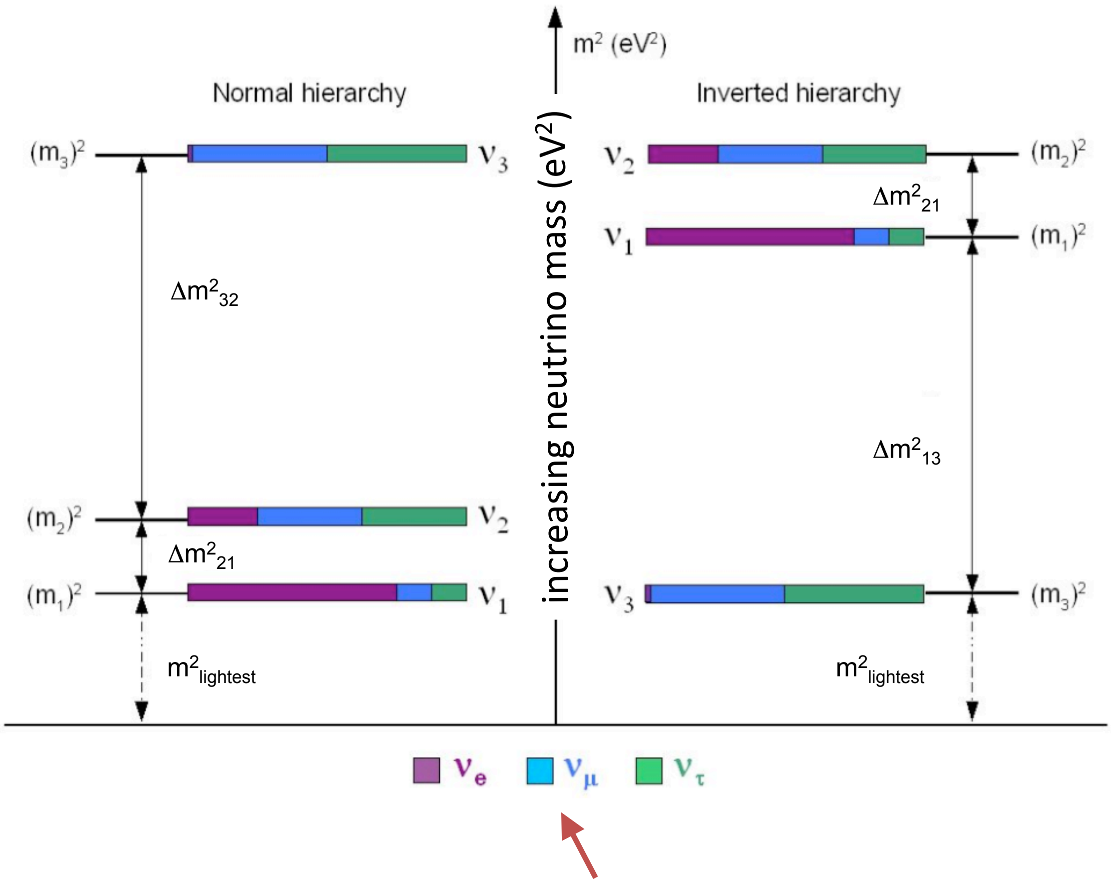
$$\theta_{23} \approx 45^\circ$$

$$\theta_{13} \approx 9^\circ$$

$$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$$

$$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$$

$$\delta_{CP} = \ ?$$



flavor content of the mass eigenstates determined by mixing matrix elements (mixing angles) that are measured experimentally

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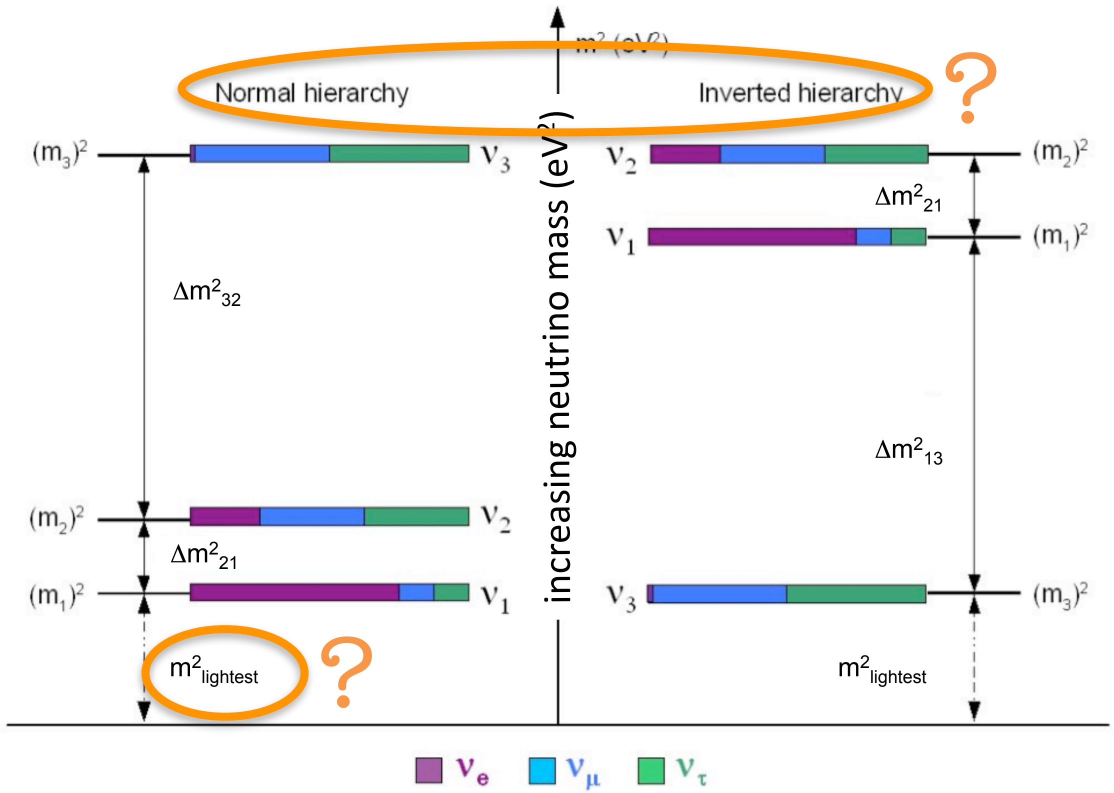


flavor content of the mass eigenstates determined by mixing matrix elements (mixing angles) that are measured experimentally

Why 3 Weak Flavor States?

Phys. Reports 427, 257 (2006)

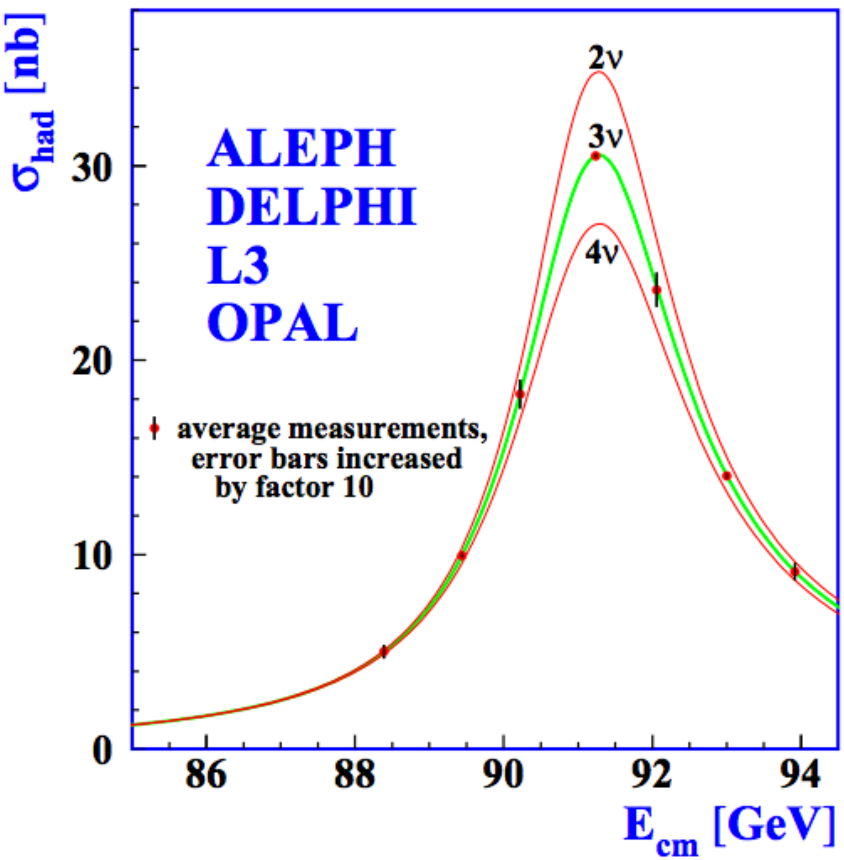


Figure 1.13: Measurements of the hadron production cross-section around the Z resonance. The curves indicate the predicted cross-section for two, three and four neutrino species with SM couplings and negligible mass.

Precision Electroweak Measurements on the Z Resonance

The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1]
the LEP Electroweak Working Group,[2]
the SLD Electroweak and Heavy Flavour Groups

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\text{SM}} = 2.984 \pm 0.008$$

The Liquid Scintillator Neutrino Detector

The “LSND Anomaly”

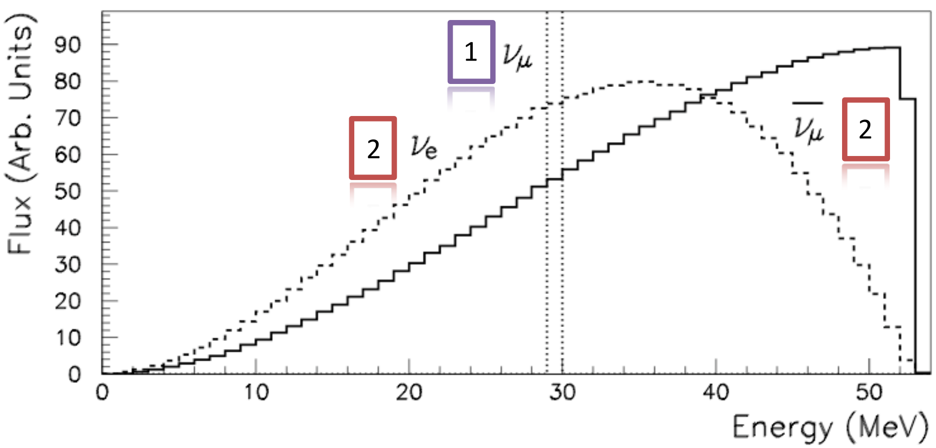
Liquid Scintillator Neutrino Detector (LSND)

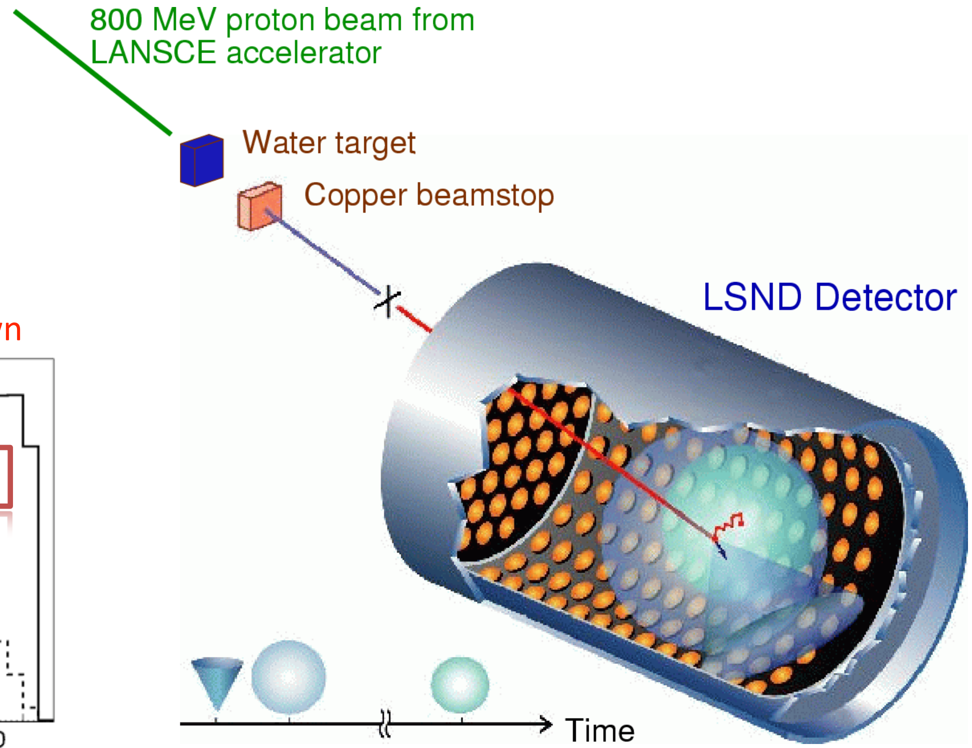
1 $\pi^+ \rightarrow \mu^+ \nu_\mu$

2 $\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$

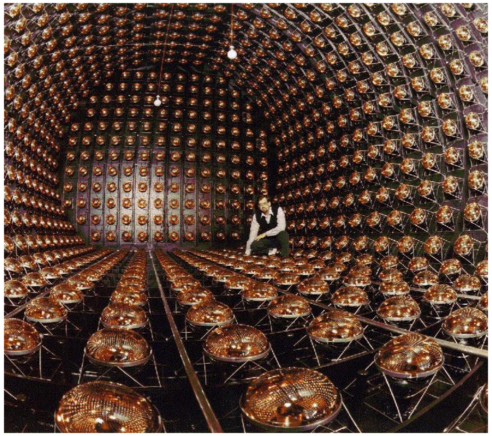
$\hookrightarrow^{?} \bar{\nu}_e$

Beam produced by decays *at rest* is precisely known





neutron captures to produce a 2.2 MeV gamma

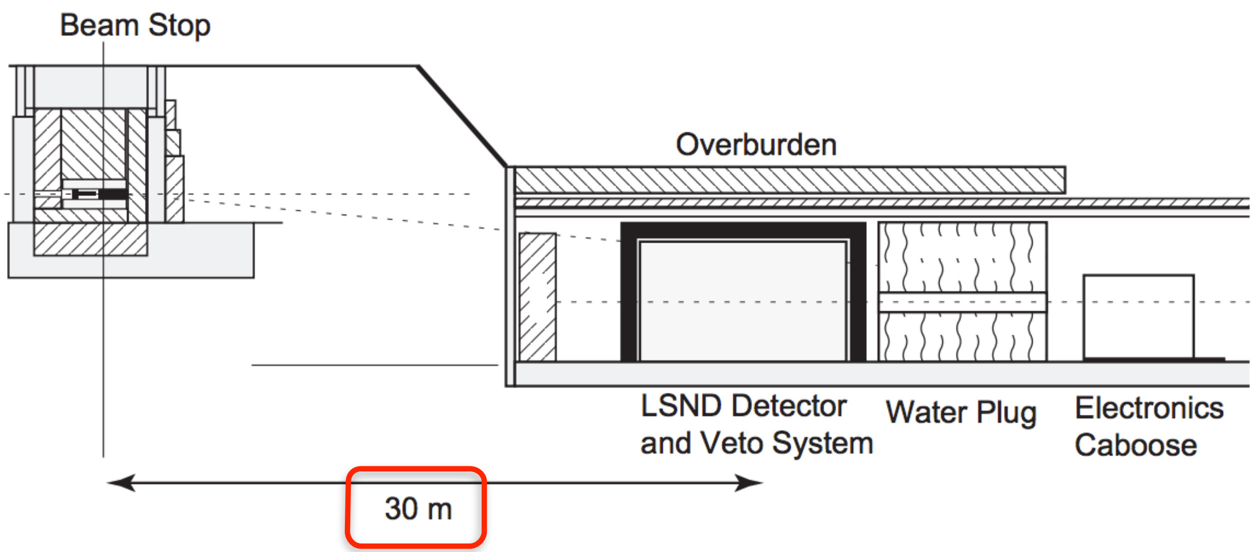


Look for electron anti-neutrinos in a beam with well-predicted fluxes and small electron anti-neutrino background

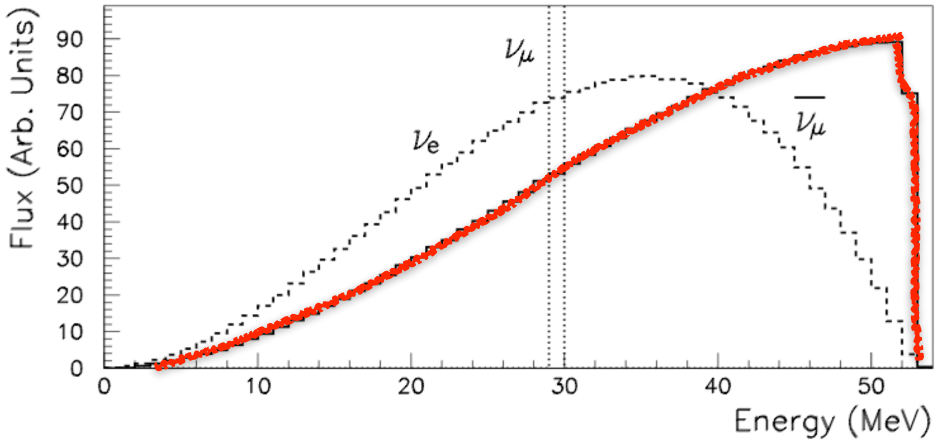
$\bar{\nu}_e$ **detection via inverse-beta-decay:** $\bar{\nu}_e + p \rightarrow e^+ + n$
(coincidence signal)

Phys. Rev. D64 (2001) 112007

Liquid Scintillator Neutrino Detector (LSND)



L



E

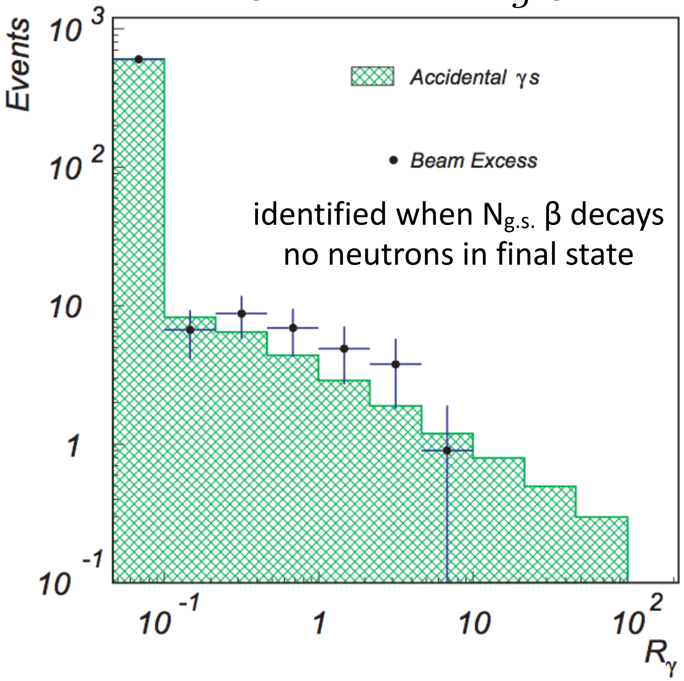
$$L/E \sim 1 \ \ \mathrm{m/MeV}$$

Phys. Rev. D64 (2001) 112007

Liquid Scintillator Neutrino Detector (LSND)

- Accidental photons possible from radioactivity sources near the detector
- Likelihood variable depends on γ energy, Δr the γ-e^+ distance, and Δt

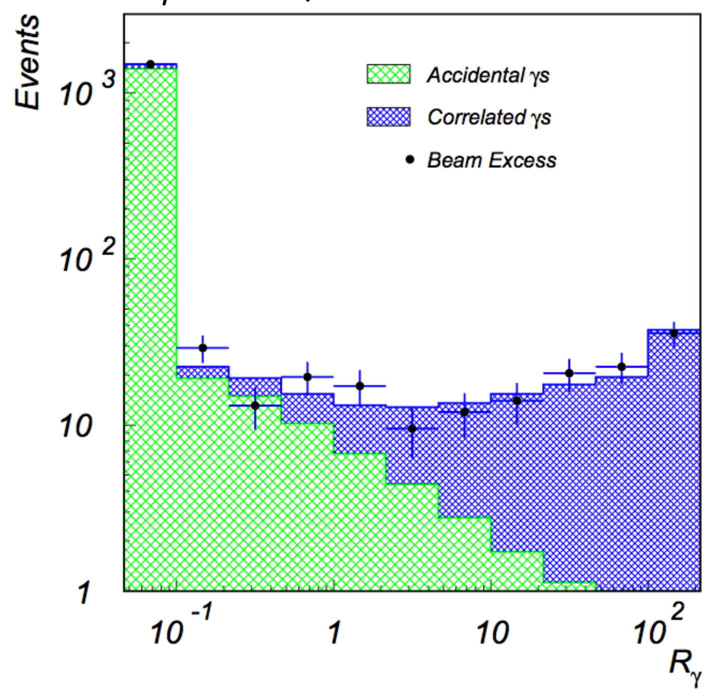
$\nu_e C \rightarrow e^- N_{g.s.}$



Expect no correlated gamma events

$$f_c = -0.004 \pm 0.007$$

$\nu_\mu C$ $\nu_\mu p$ charged-current



Expect 14% with FS neutron → correlated gamma

$$f_c = 0.129 \pm 0.013$$

Phys. Rev. D64 (2001) 112007

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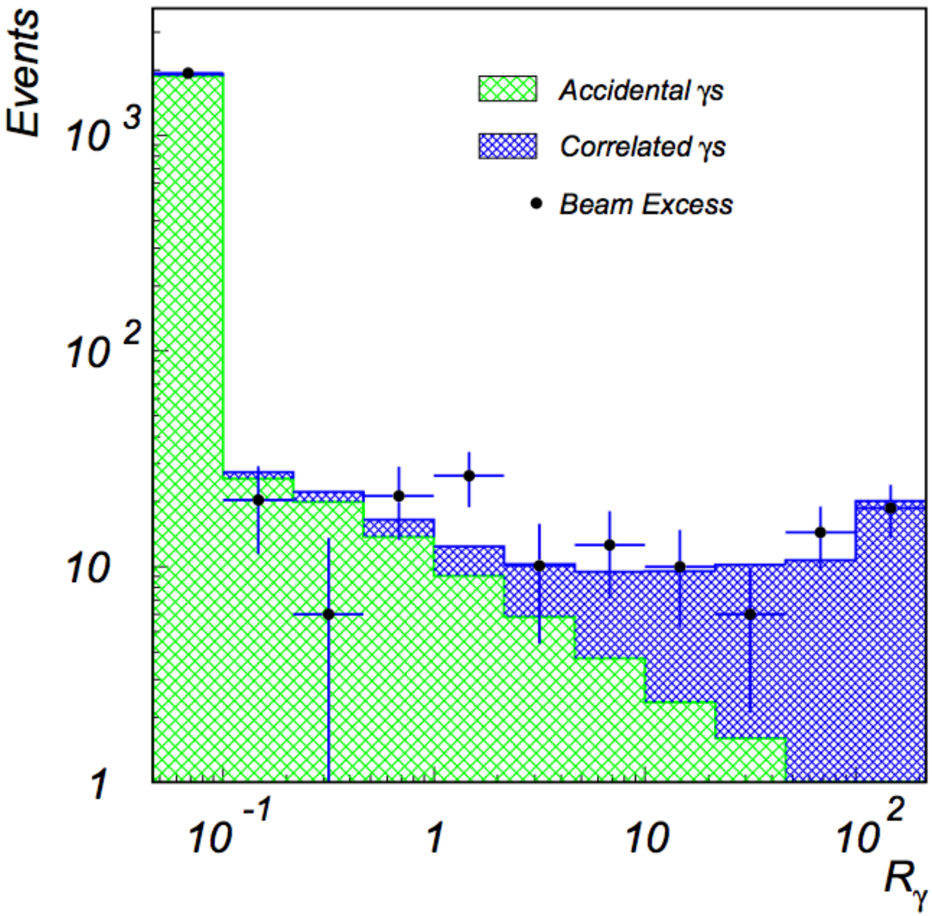

Events passing pre-cuts for having an electron/positron in the event

Fitted correlated gamma fraction:

$$f_c = 0.0567 \pm 0.0108$$

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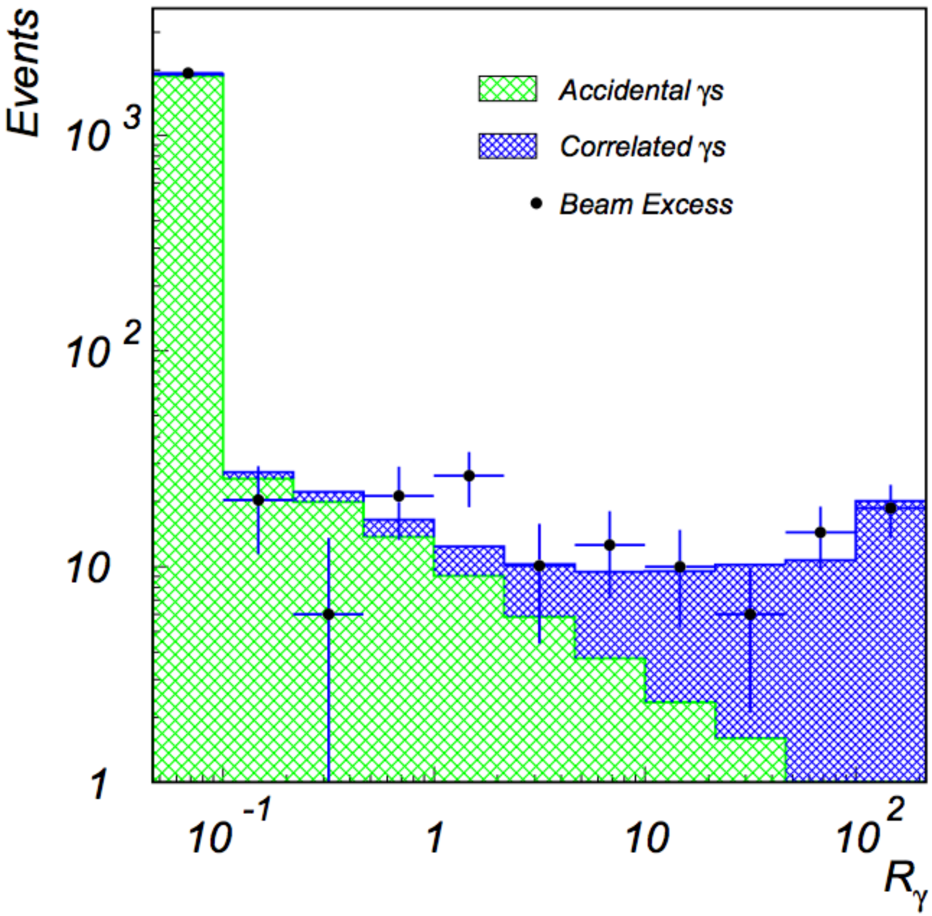

Events passing pre-cuts for having an electron/positron in the event

Fitted correlated gamma fraction:

$$f_c = 0.0567 \pm 0.0108$$

Blue histogram represents

$$117.9 \pm 22.4$$

events with correlated neutron capture gamma

$$\boxed{87.9 \pm 22.4 \pm 6.0}$$

above expectation

Phys. Rev. D64 (2001) 112007

Liquid Scintillator Neutrino Detector (LSND)

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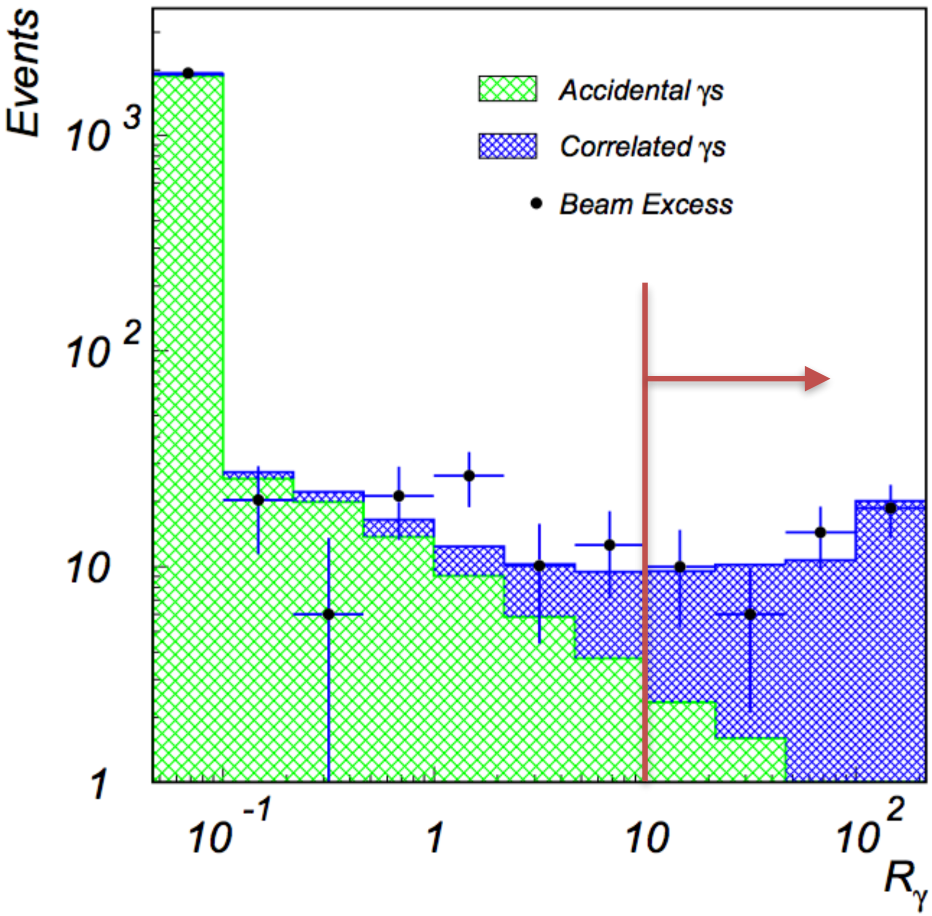
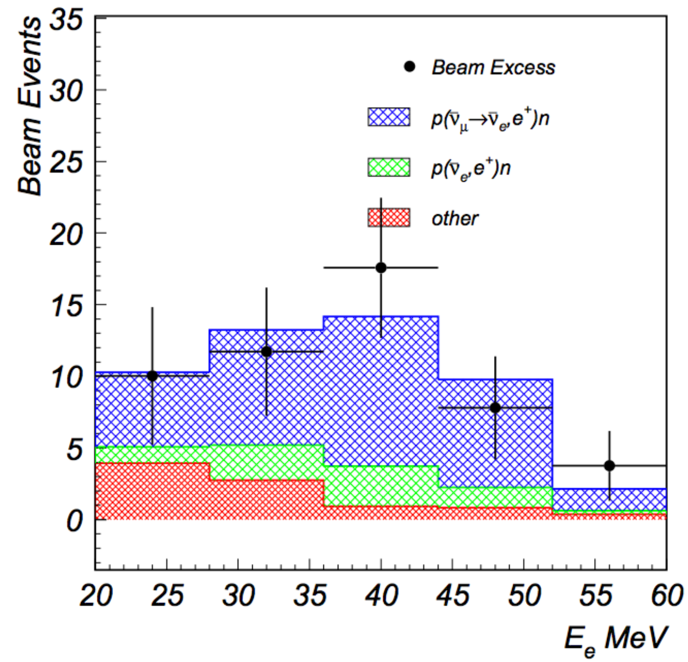


Electron energy of most signal-like events



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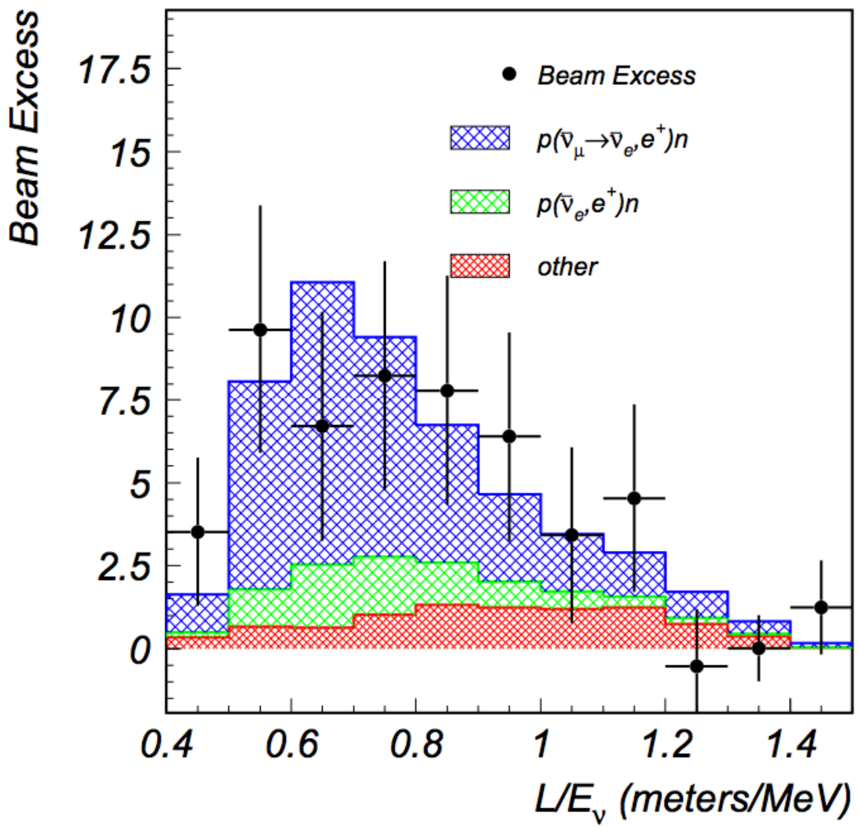
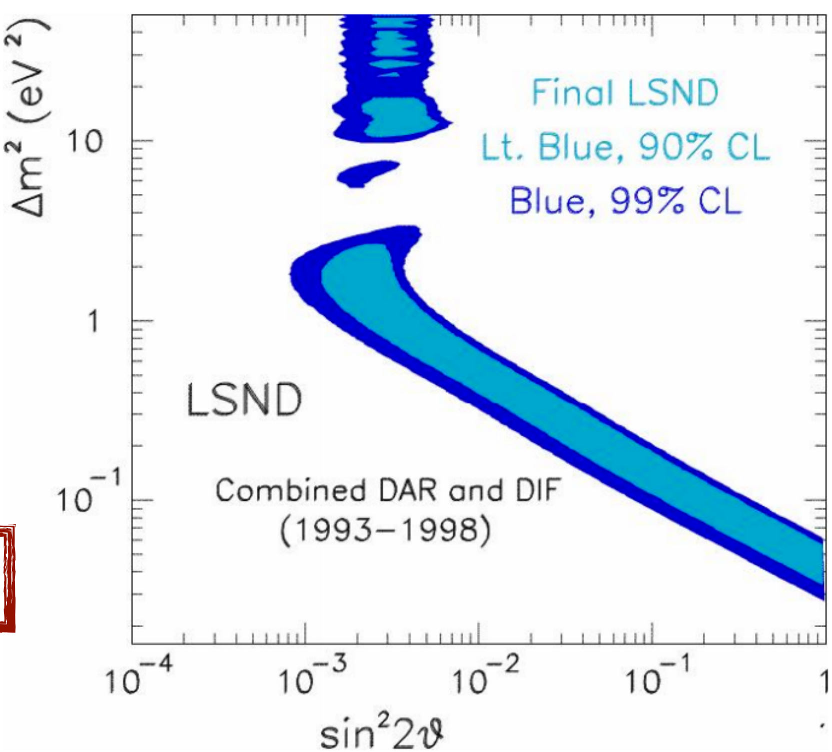


Observed excess described by best fit oscillation probability:

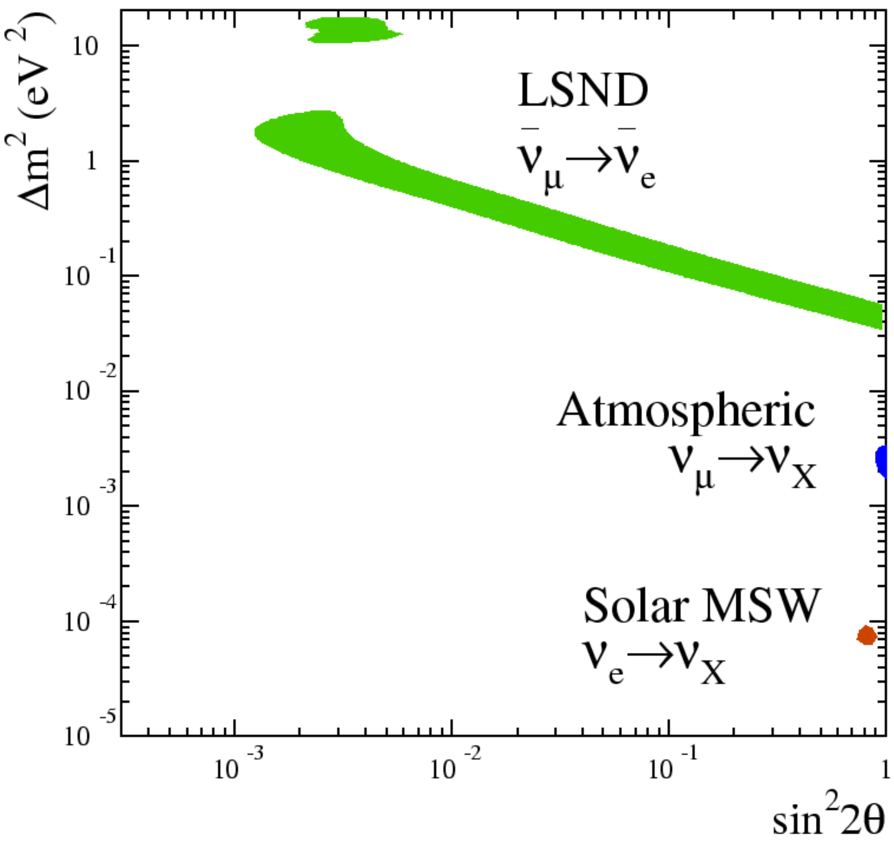
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$



L/E distribution of the most signal-like events

Phys. Rev. D64 (2001) 112007

Accommodating the LSND Result

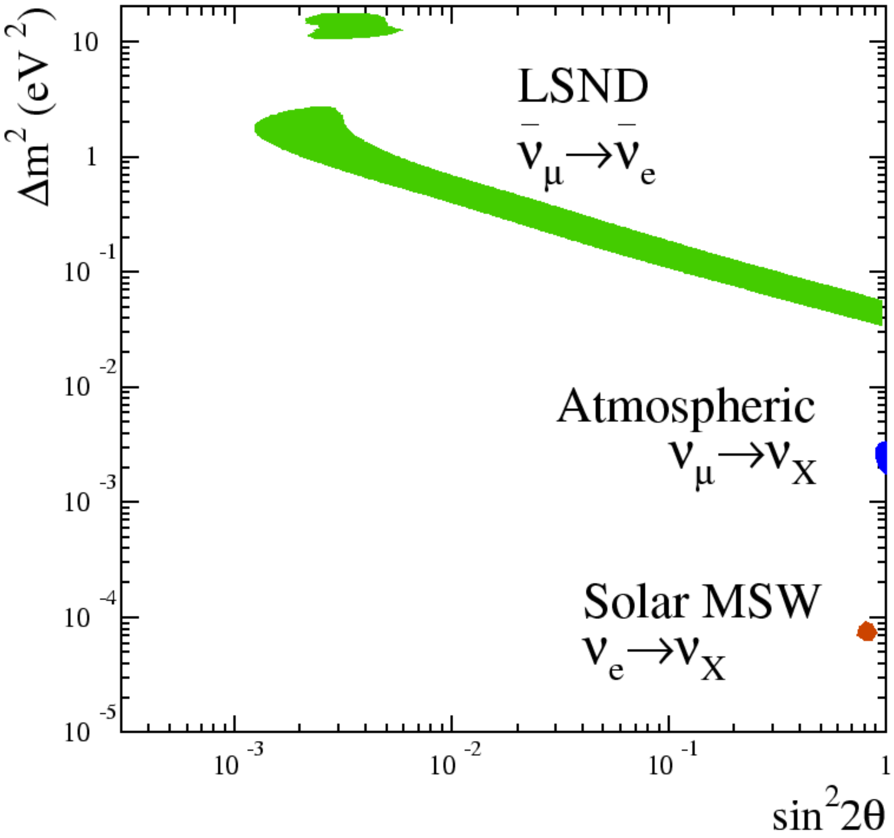


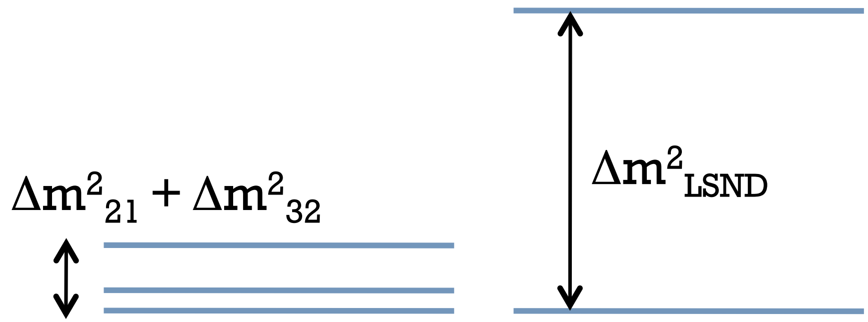
Δm^2_{LSND} $\quad L/E \sim 1$ km/GeV

$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$ $\quad L/E = 500$ km/GeV

$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$ $\quad L/E = 15{,}000$ km/GeV

Accommodating the LSND Result





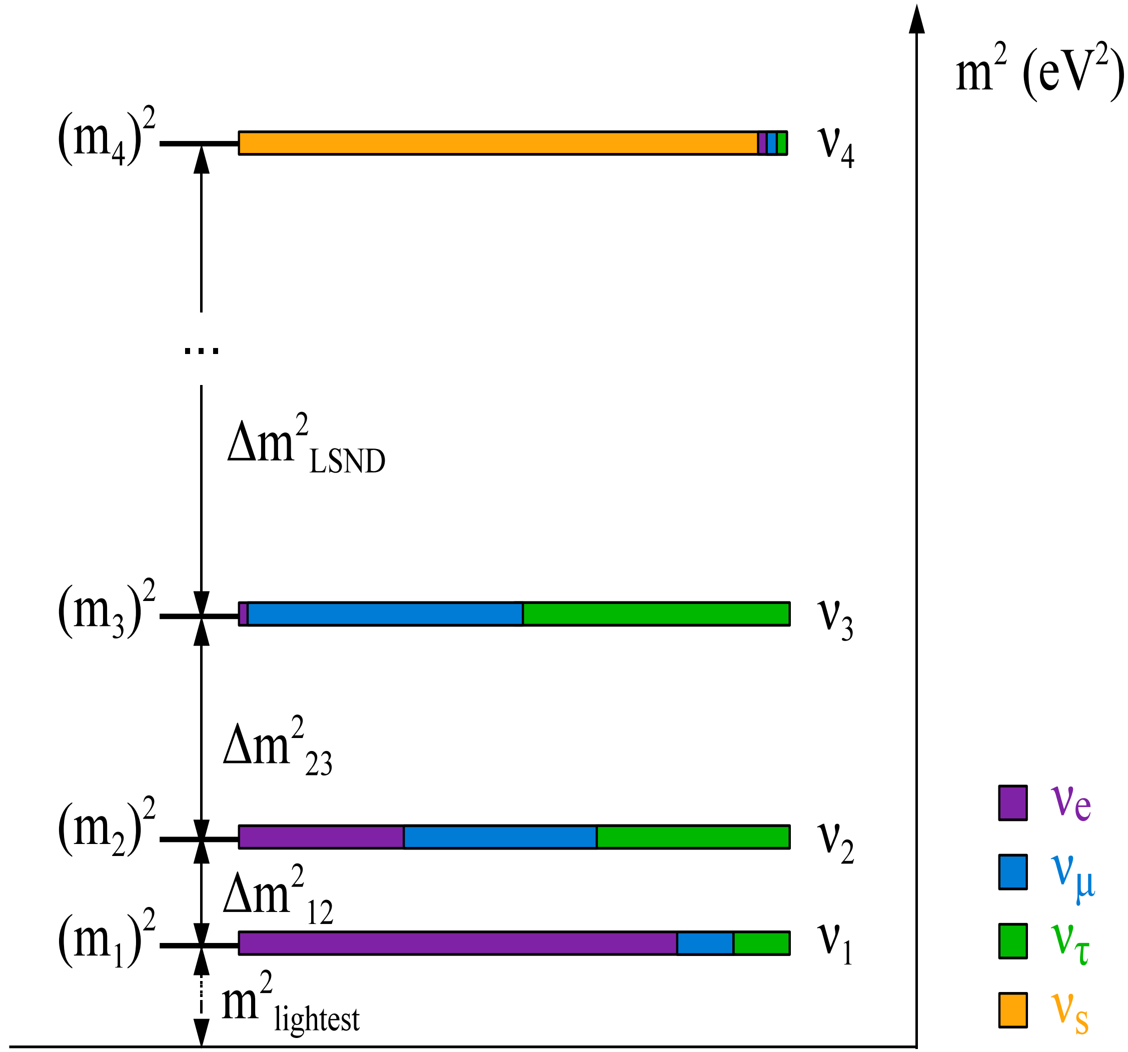
$\Delta m^2_{LSND} >> \Delta m^2_{21} + \Delta m^2_{32}$

Accommodating the LSND Result

Sterile neutrino

Additional neutrino flavor and mass state that has no weak interactions through the standard W/Z bosons

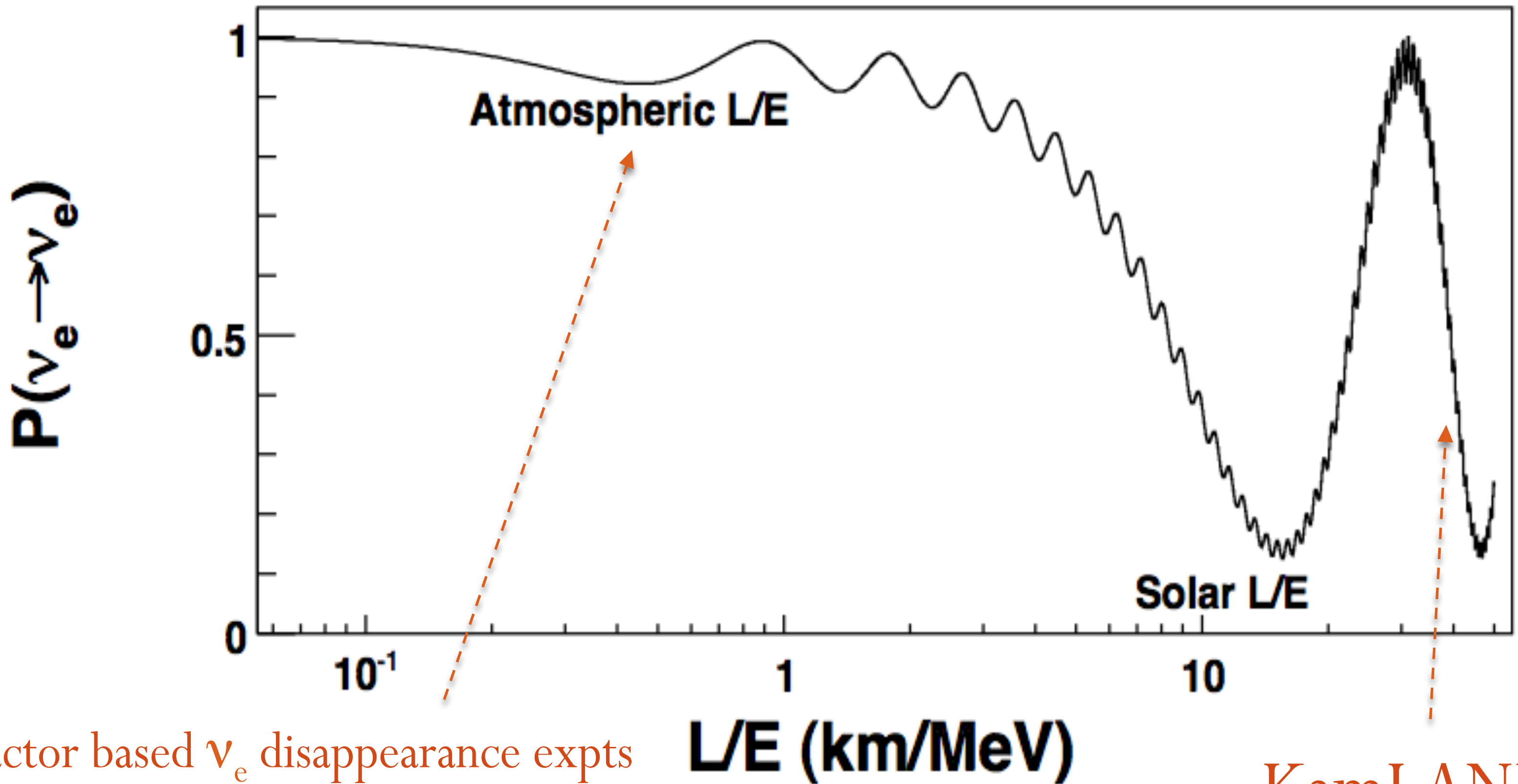
Mass state accessed only through mixing with standard model neutrinos



Reactor Neutrinos at very Short-Baseline

The “Reactor Anomaly”

Oscillations with Reactor Neutrinos



Reactor based ν_e disappearance expts such as Double Chooz and Daya Bay

KamLAND

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27 \cdot \Delta m^2_{23} \cdot L/E)$$

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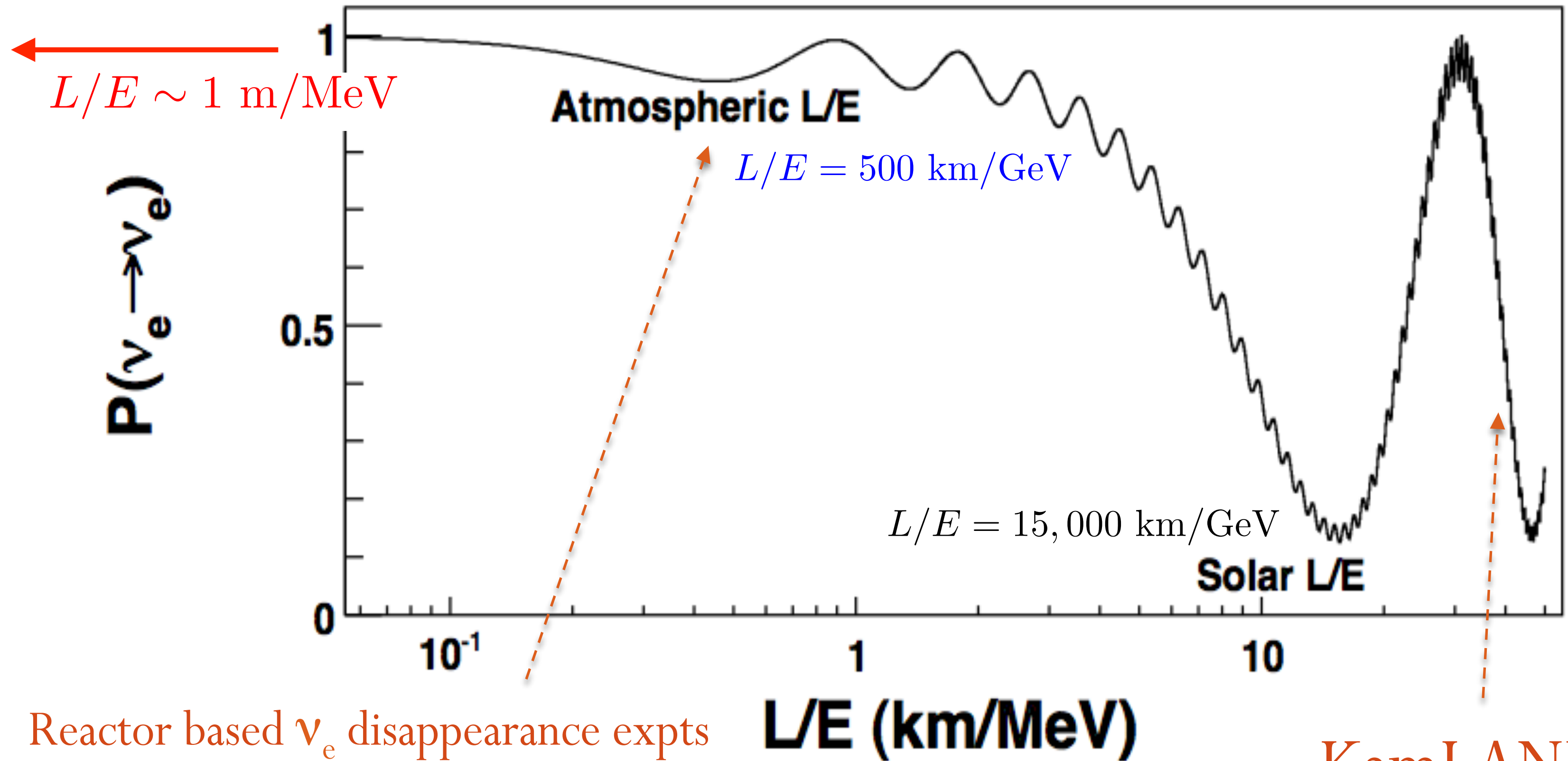
Oscillations with Reactor Neutrinos



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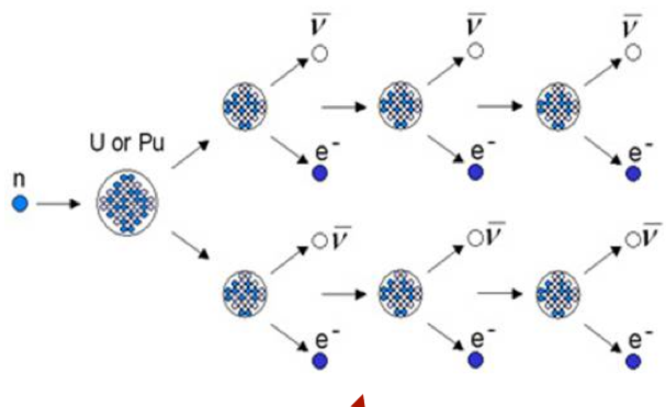
Reactor Neutrino Experiments

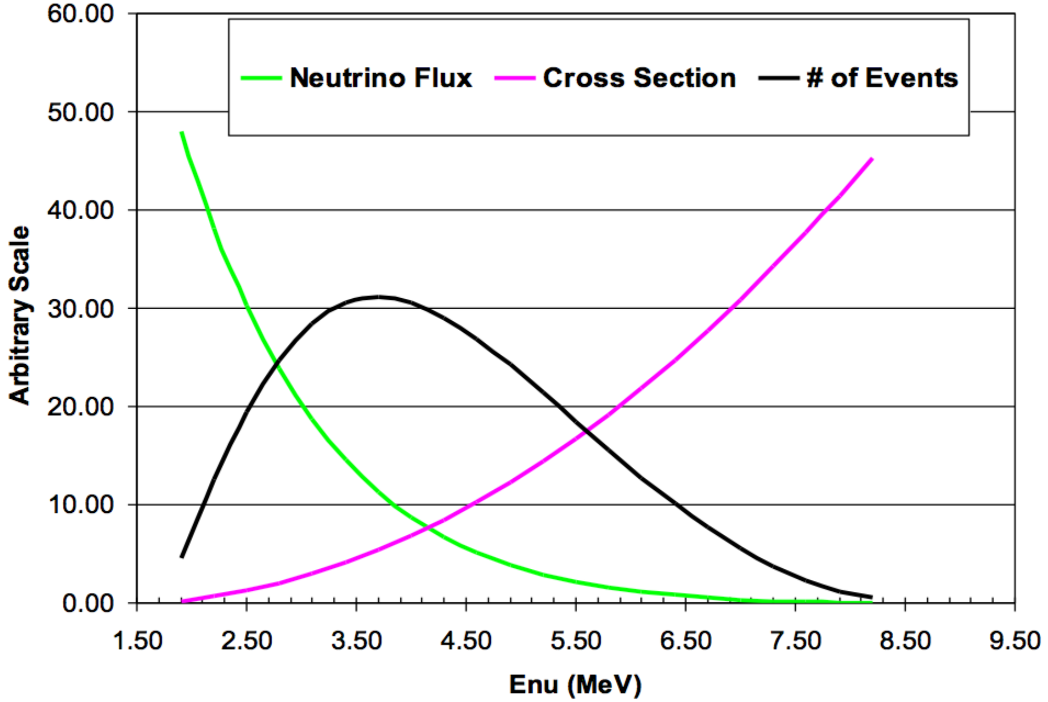
Reactor $\bar{\nu}_e$ production



β^- decay of neutron rich fission fragments of U and Pu

Detection through inverse β Decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



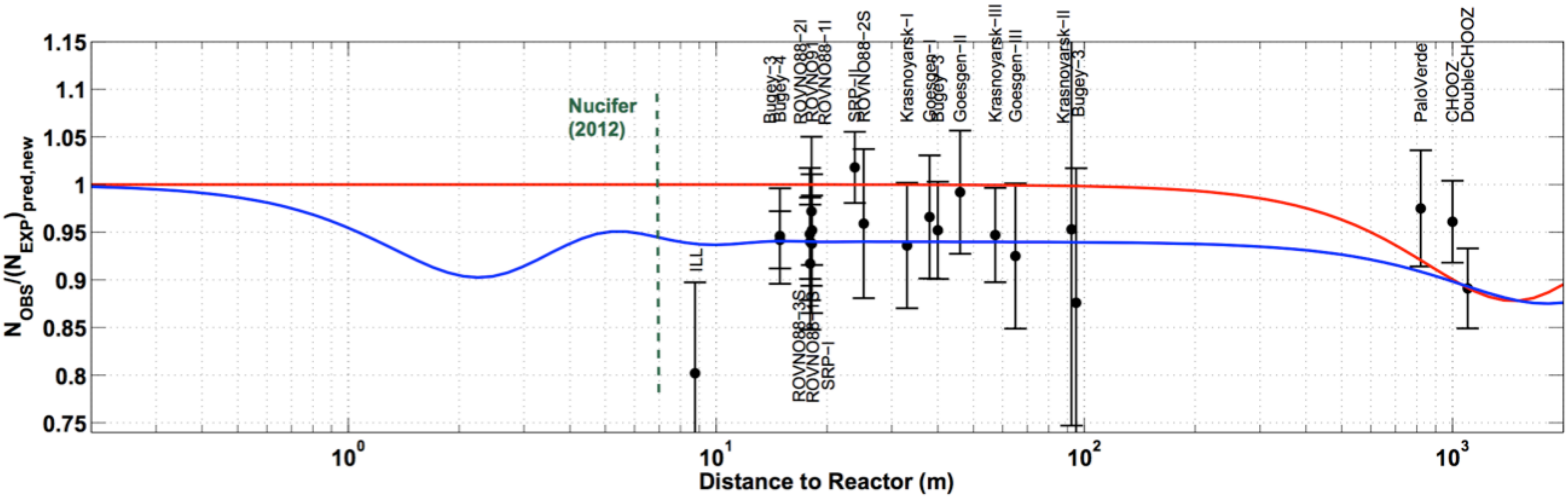
$E_{prompt} = E_\nu - 0.8$ MeV

Reactor Neutrino Anomaly

- In preparation for Double Chooz analysis with a single far detector, Mueller et al. applied an improved procedure to go from measured ^{235}U, ^{239}Pu, and ^{241}Pu β^- spectra (at ILL) to neutrino spectra.
  - Th. A. Mueller et al. “Improved Predictions of Reactor Antineutrino Spectra” Phys. Rev. C83 (2011) 054615; arXiv:1101.2663.
- Result was a net 3% increase in the estimated fluxes relative to previous predictions, reanalysis of past reactor experiments
  - G. Mention et al. “The Reactor Antineutrino Anomaly”, Phys. Rev. D83 (2011) 083006; arXiv:1101.2755.
- P. Huber, using a different method to go from β- to neutrino spectra, finds a similar shift
  - P. Huber, “On the determination of anti-neutrino spectra from nuclear reactors”; arXiv:1106.0687.

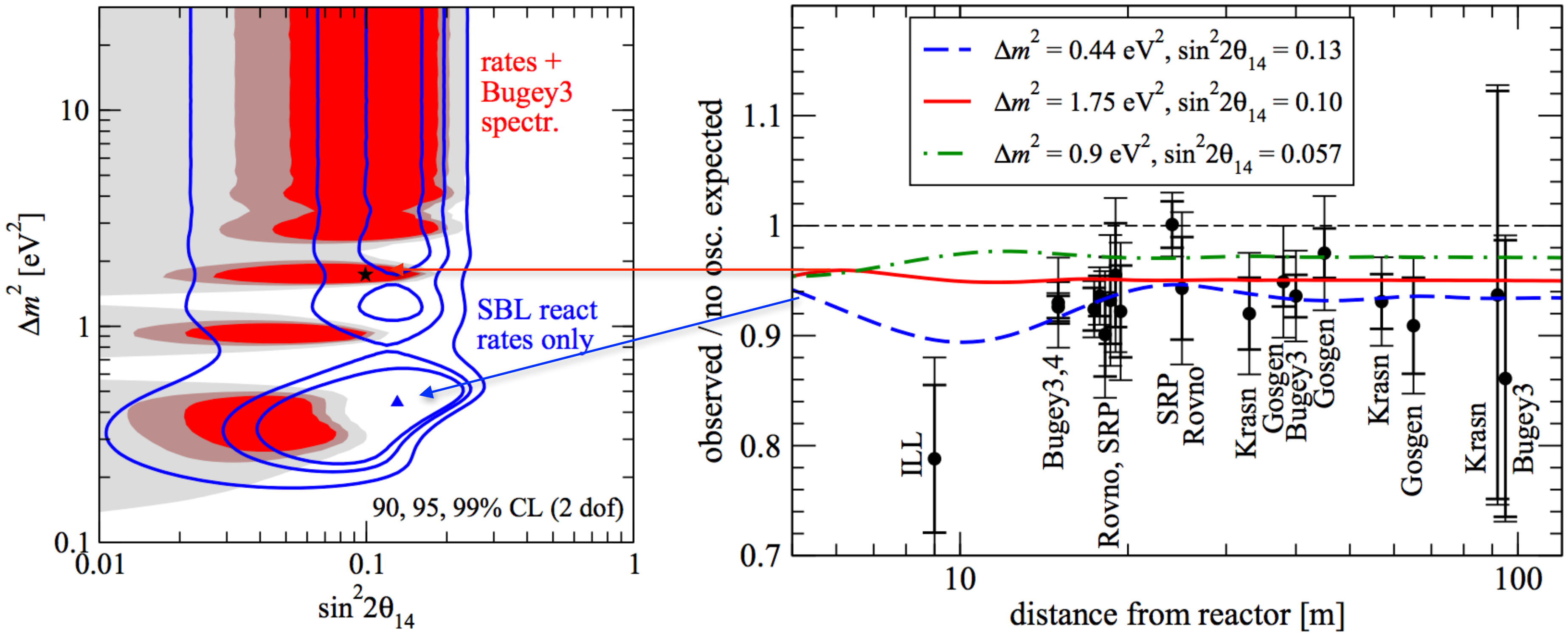
Reactor Neutrino Anomaly

L/E ~ 2-3 m/MeV   L/E ~ 25-30 m/MeV



- Looked back at ratio of the observed to predicted $\overline{\nu}_e$ event rate for 19 different reactor neutrino experiments at baselines less that 100 m.
- Mean average ratio including correlations is 0.927 ± 0.023, indicating a 7.3% deficit at short baseline.
- Curves show fits to data assuming standard 3 neutrino oscillations and assuming oscillations with one additional sterile neutrino

Reactor Neutrino Anomaly



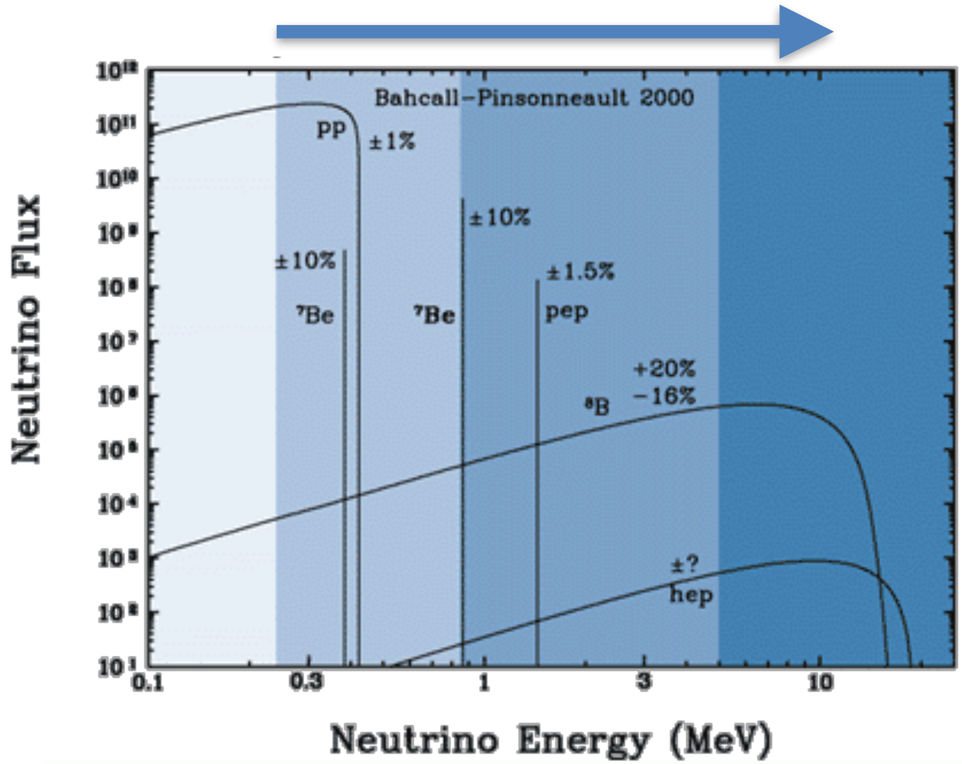
- Global fit to reactor data from J. Kopp et al. “Sterile Neutrino Oscillations: the global picture”, arXiv:1303.3011.

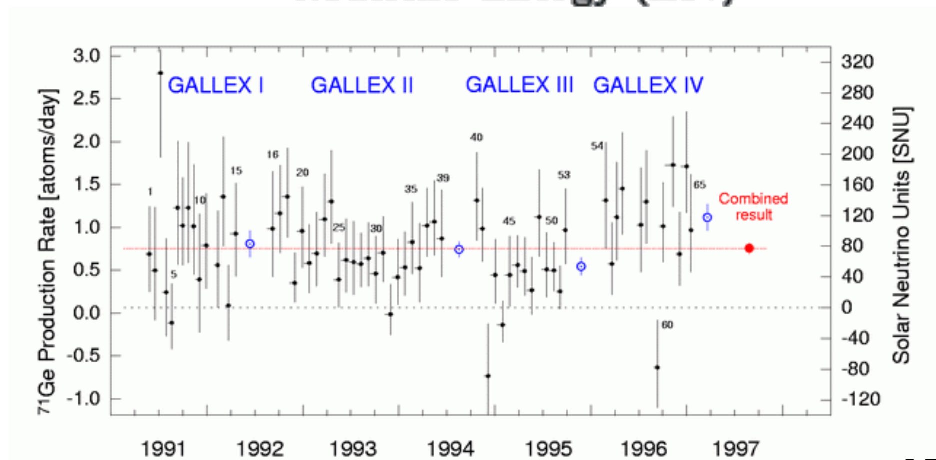
Source Calibration Data at Gallium Solar Neutrino Experiments

The “Gallium Anomaly”

GALLEX and SAGE Solar Neutrino Expts

- GALLEX and SAGE were solar neutrino experiments built in the 1990s
  - Detect solar neutrinos above 233 keV by the inverse β-decay reaction $^{71}Ga(\nu_e,e^-)^{71}Ge$
- GALLEX (Gallium Experiment) ran at the Gran Sasso Underground Laboratory in Italy
  - 30 tons of gallium in the form of $GaCl_3$-HCl
- SAGE (RuSsian-American Gallium Experiment) located in Baksan Neutrino Observatory in Russia
  - 60 tons of gallium metal

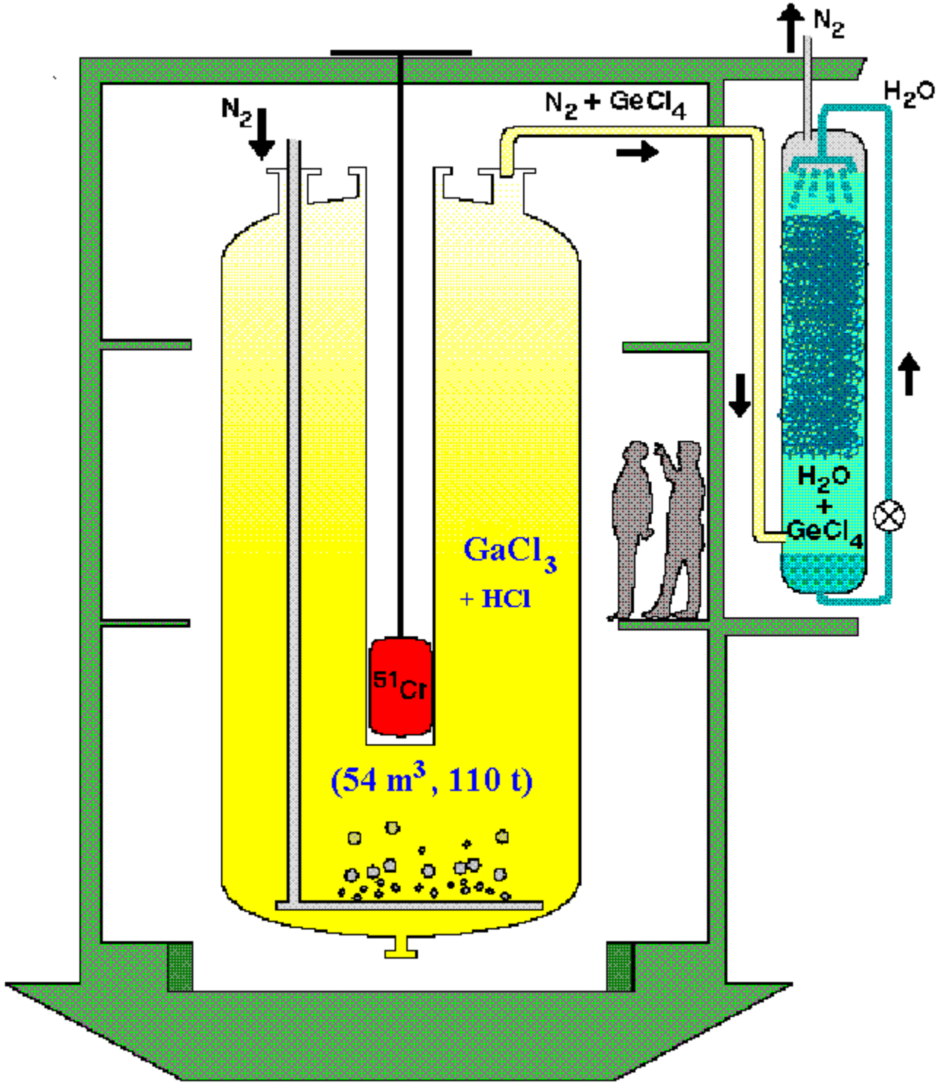




GALLEX and SAGE Source Calibration

- They measured solar neutrino rates well below the prediction, which of course we now know to be oscillations
- To understand their absolute efficiencies, they calibrated their detectors with low energy neutrino sources - running with Cr-51 or Ar-37 sources
  - Cr-51, for example, produces 750 keV (90%) and 430 keV (10%) neutrinos
  - Ar-37 produces an 811 keV neutrino
- This amounts to an experiment with very low energy neutrinos (100s keV) over a very short baseline (~1-few meters)

$$\nu_e \to \nu_x$$



GALLEX

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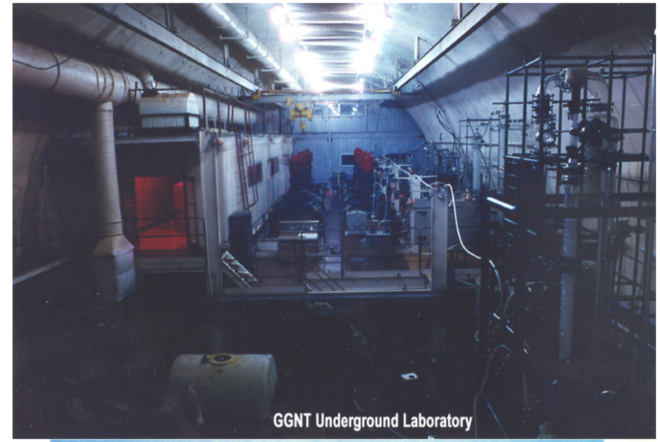
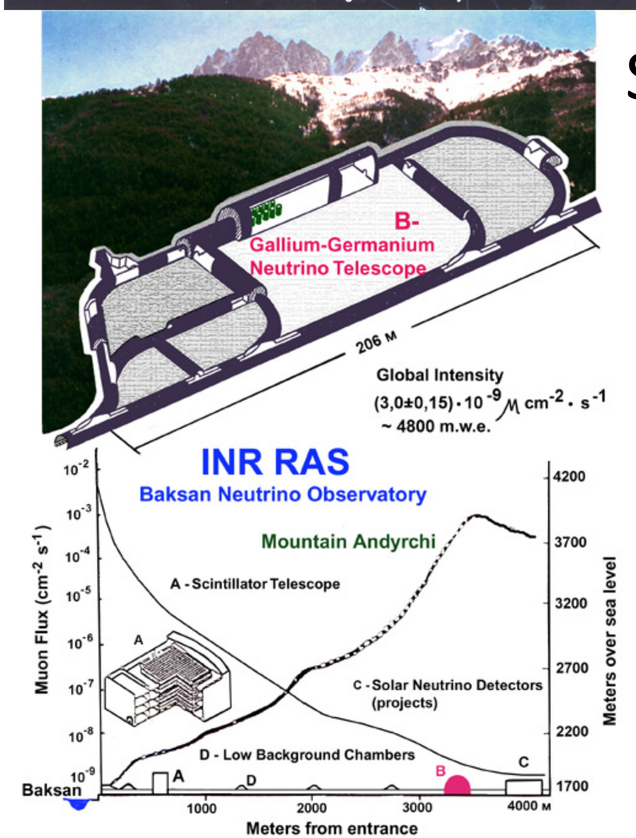




SAGE

GALLEX and SAGE Source Calibration

- No spectral information, just total event counts compared to prediction

GALLEX

SAGE

$$R_1(Cr) = 0.94 \pm 0.11 \quad R_3(Cr) = 0.93 \pm 0.12$$

$$R_2(Cr) = 0.80 \pm 0.10 \quad R_4(Ar) = 0.77 \pm 0.08$$

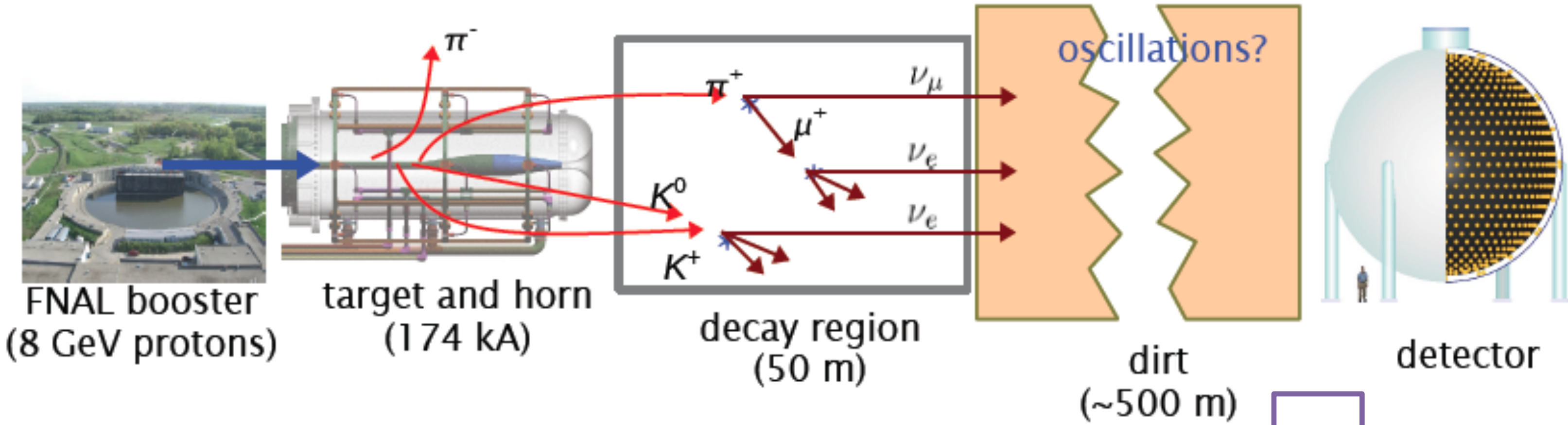
$$\boxed{R = 0.86 \pm 0.05}$$

GALLEX: F. Kaether, W. Hampel, G. Heusser, J. Kiko, and T. Kirsten, Phys.Lett. B685 (2010) 47-54. [arXiv:1001.2731].
SAGE Cr: J. Abdurashitov et al., Phys. Rev. C59 (1999) 2246-2263. [hep-ph/9803418].
SAGE Ar: J. Abdurashitov, V. Gavrin, S. Girin, V. Gorbachev, P. Gurkina, et al., Phys. Rev. C73 (2006) 045805, [nucl-ex/0512041].

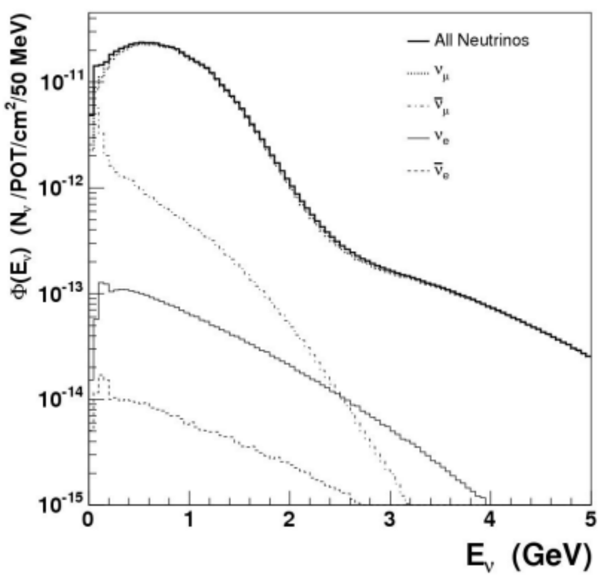
MiniBooNE Neutrino and Antineutrino Results

MiniBooNE

- Designed to follow up on the LSND result as oscillations but with different source, different detections, thus different systematics



$\boxed{L}$



$\boxed{E}$

$$L/E \sim 1 \ \ \mathrm{m/MeV}$$

same as LSND

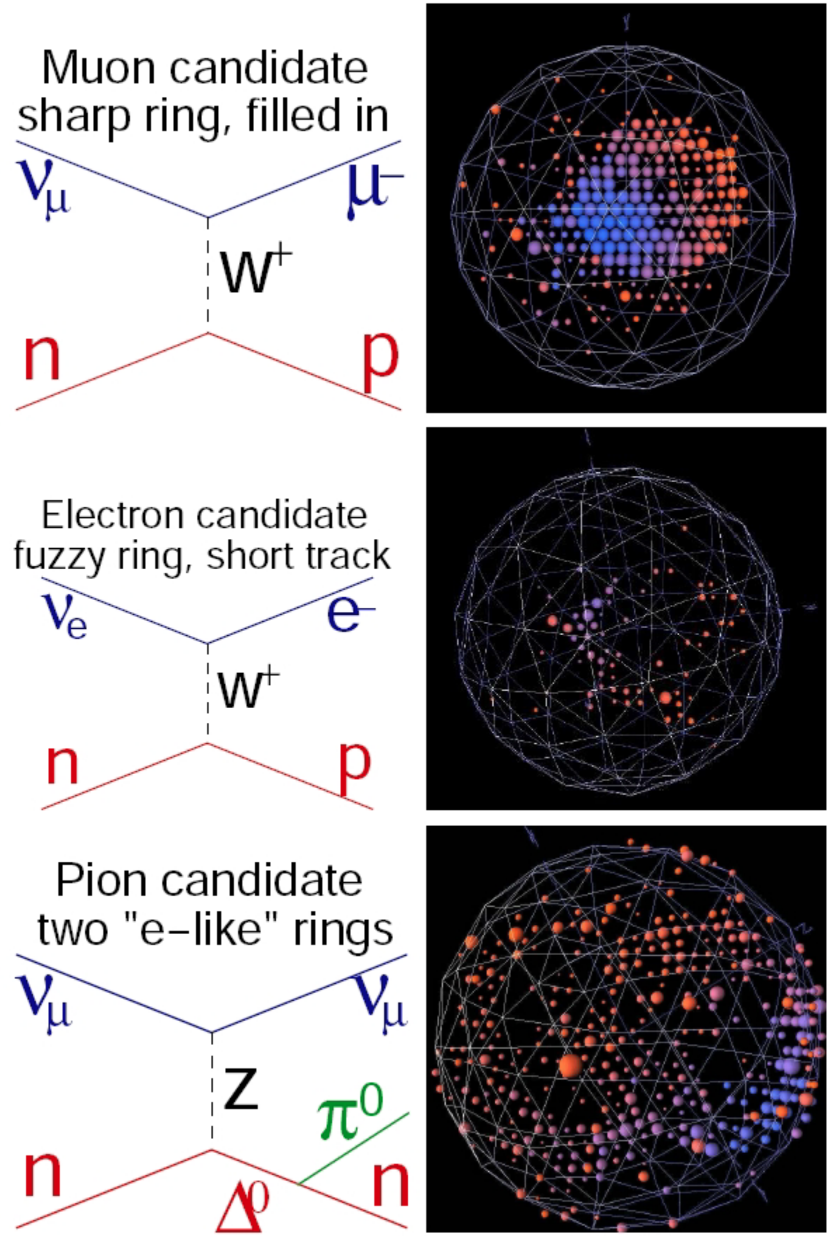
MiniBooNE

- Cherenkov detector - see Cherenkov light rings generated by charged particles
- Looking for:

$$\nu_\mu \rightarrow \nu_e$$

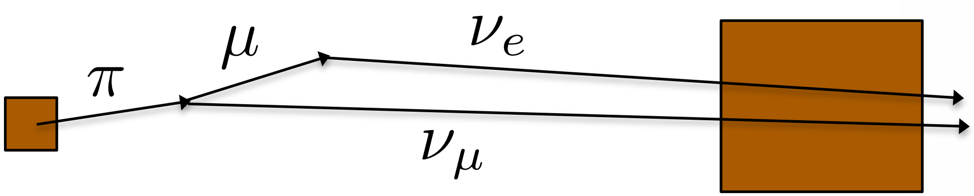
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

- Backgrounds come from small intrinsic electron neutrino rate in the beam and any ν_μ interactions that leave a single reconstructed photon in the final state
- Cherenkov detector can not distinguish electron from single gamma

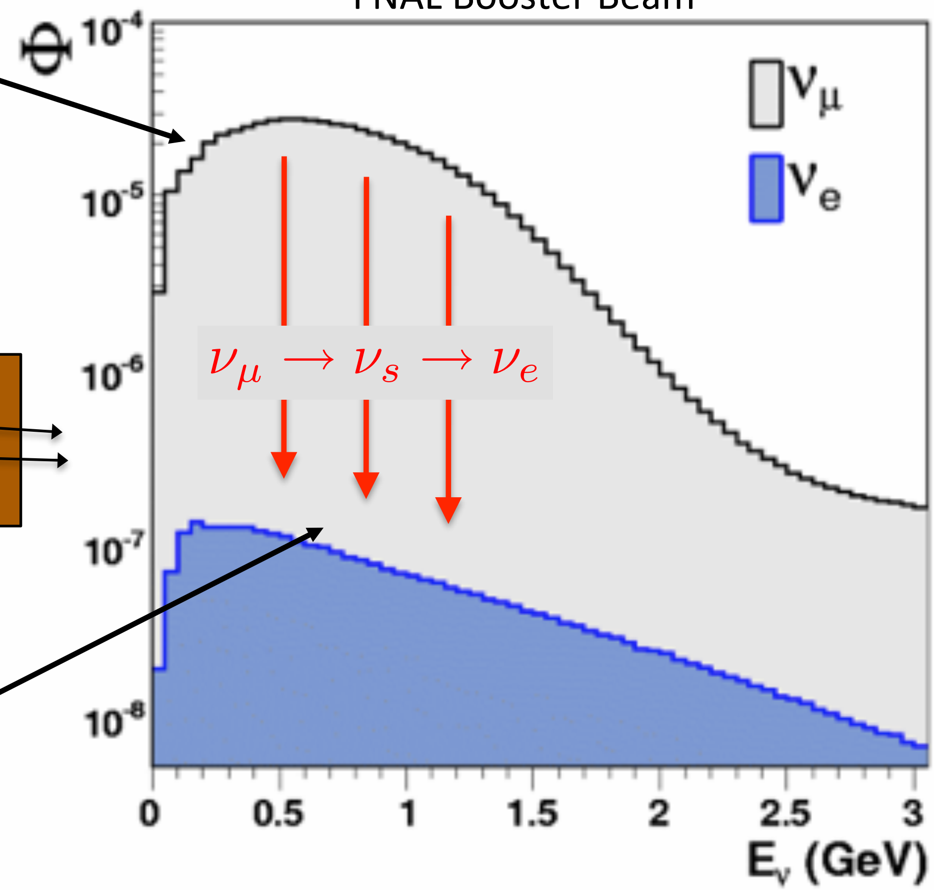


MiniBooNE - A One Detector Experiment

effectively unoscillated large-statistics muon neutrino CC sample provides a <u>constraint</u> on (*flux × xsec*) of electron neutrino CC rate



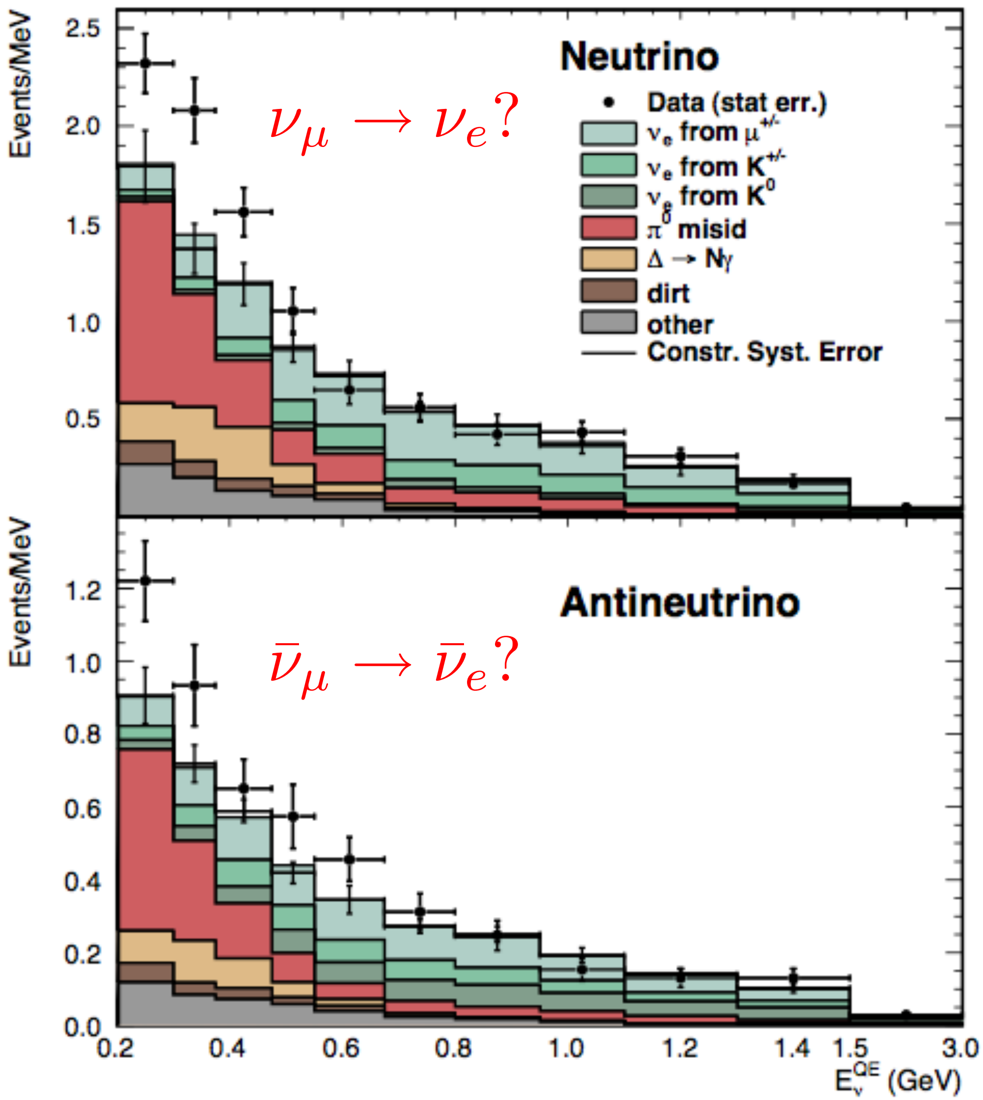
FNAL Booster Beam



look for an **excess** on top of the expected intrinsic electron neutrino CC rate

sounds simple enough…

MiniBooNE Results



<u>MiniBooNE Final Results:</u>

3.4σ excess in neutrino mode

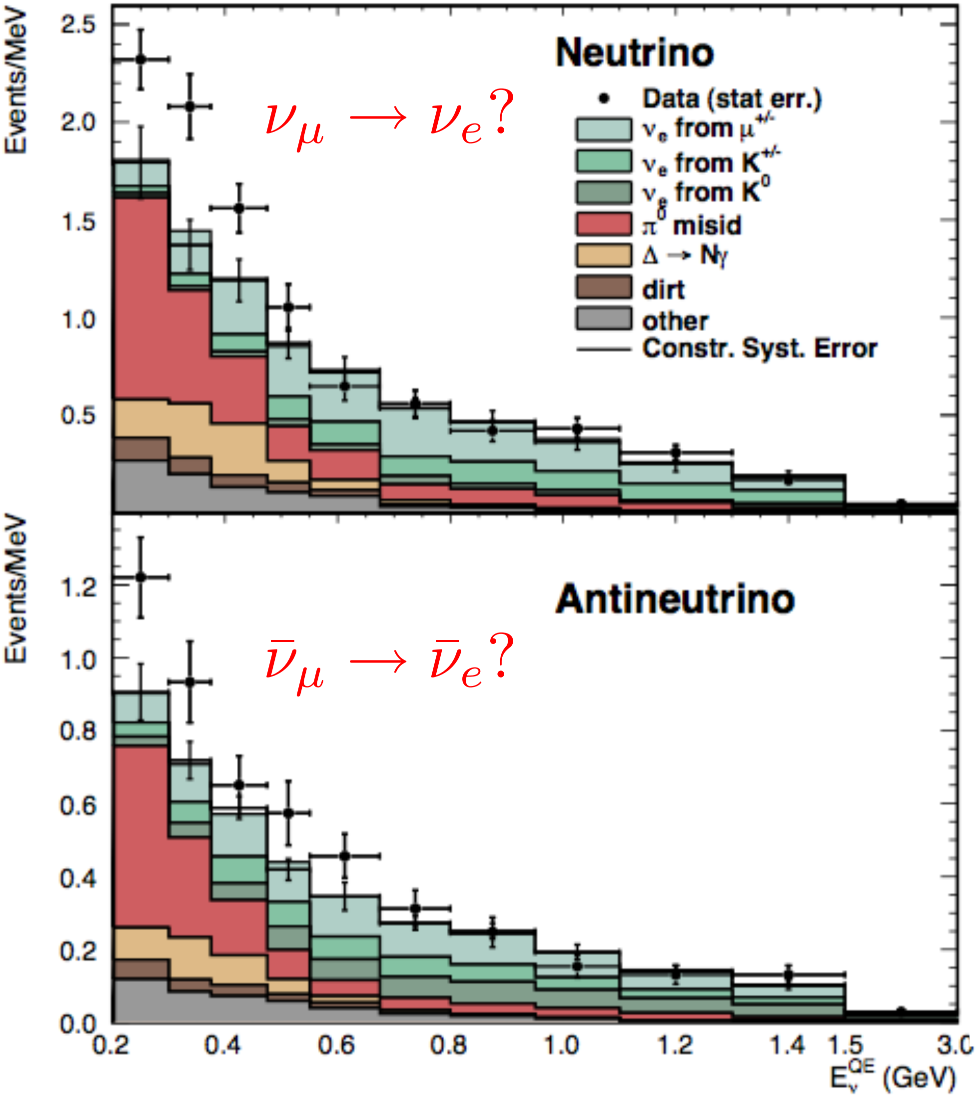
$$162.0 \pm 28.1(\text{stat}) \pm 38.7(\text{syst})$$

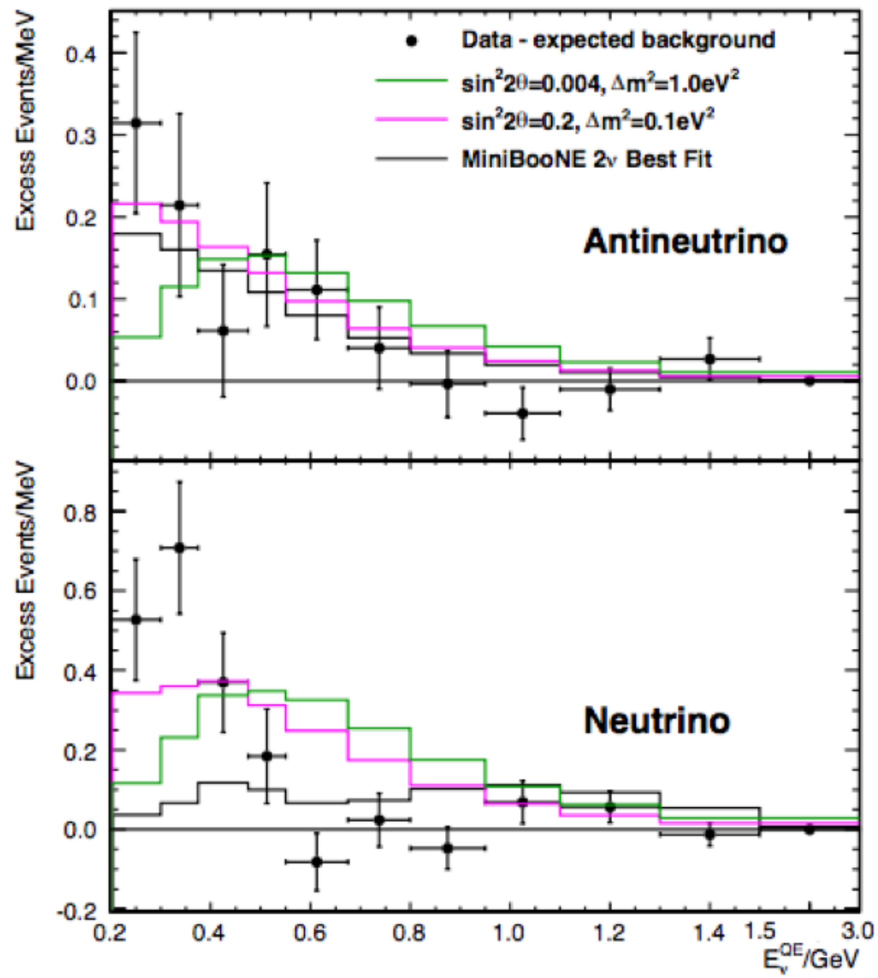
2.8σ excess in antineutrino mode

$$78.4 \pm 20.0(\text{stat}) \pm 20.3(\text{syst})$$

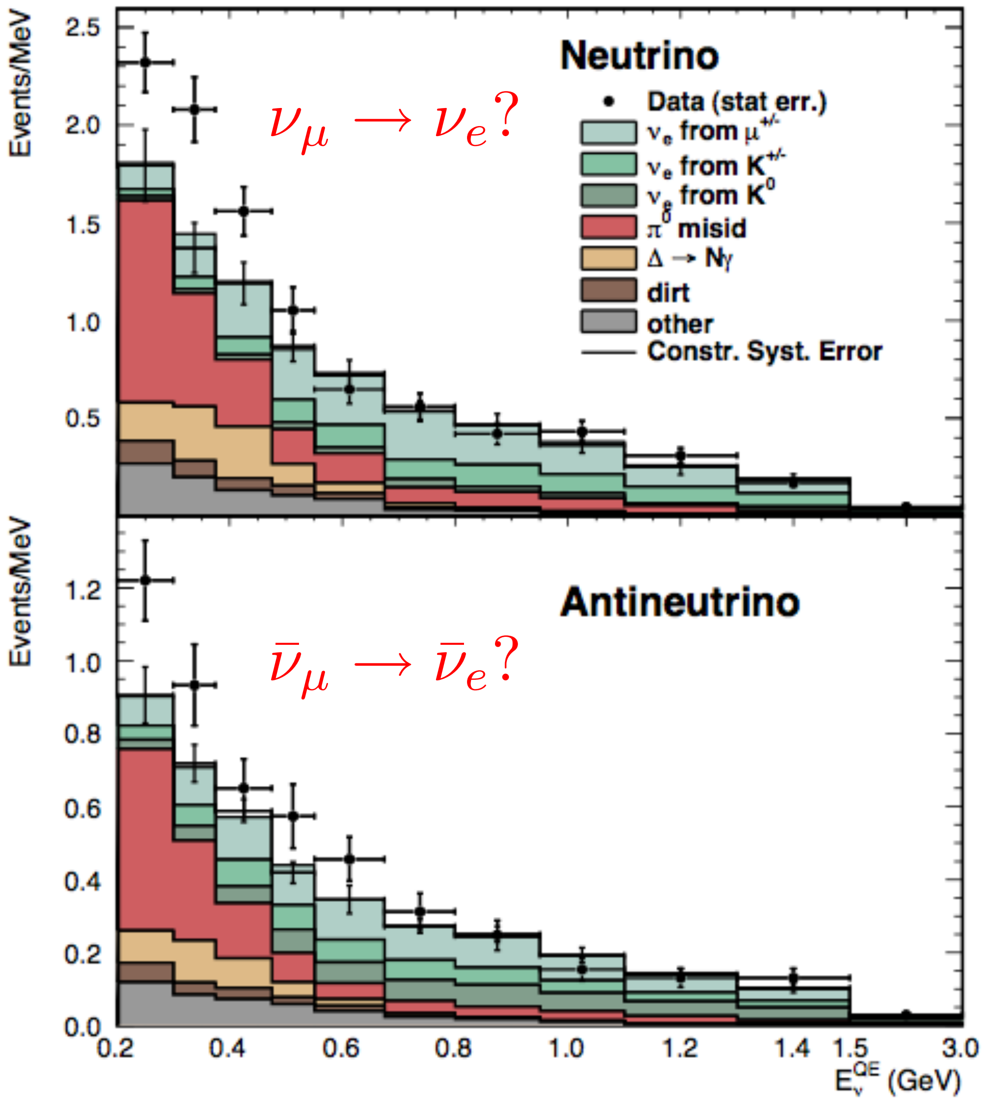
arXiv:1207.4809

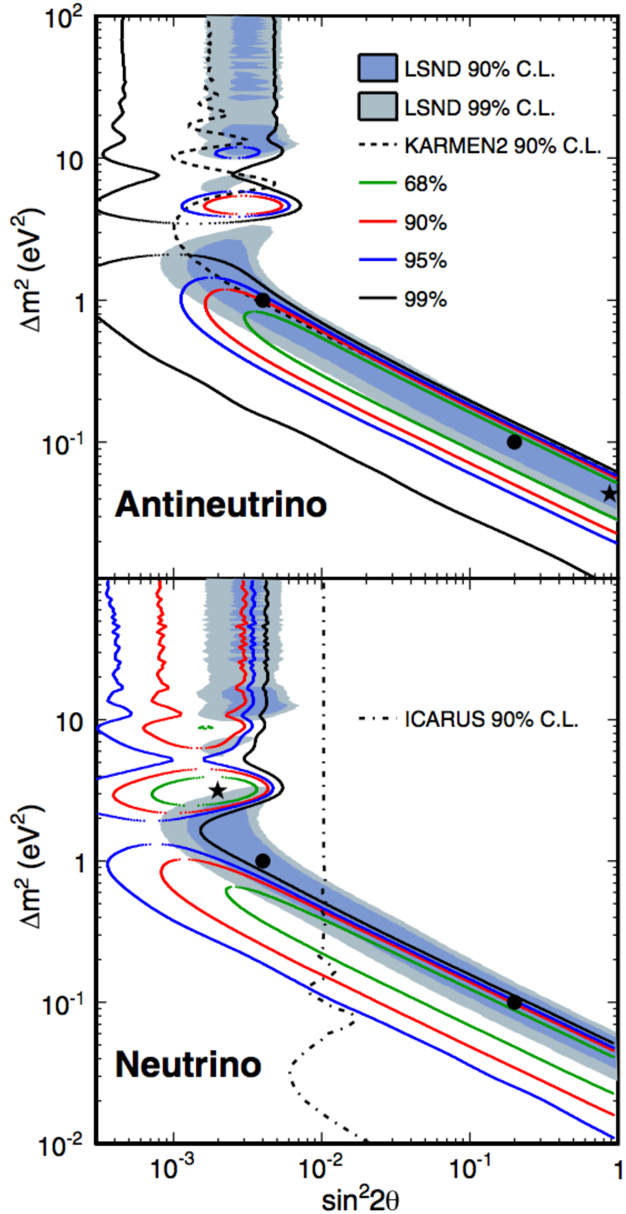
MiniBooNE Results



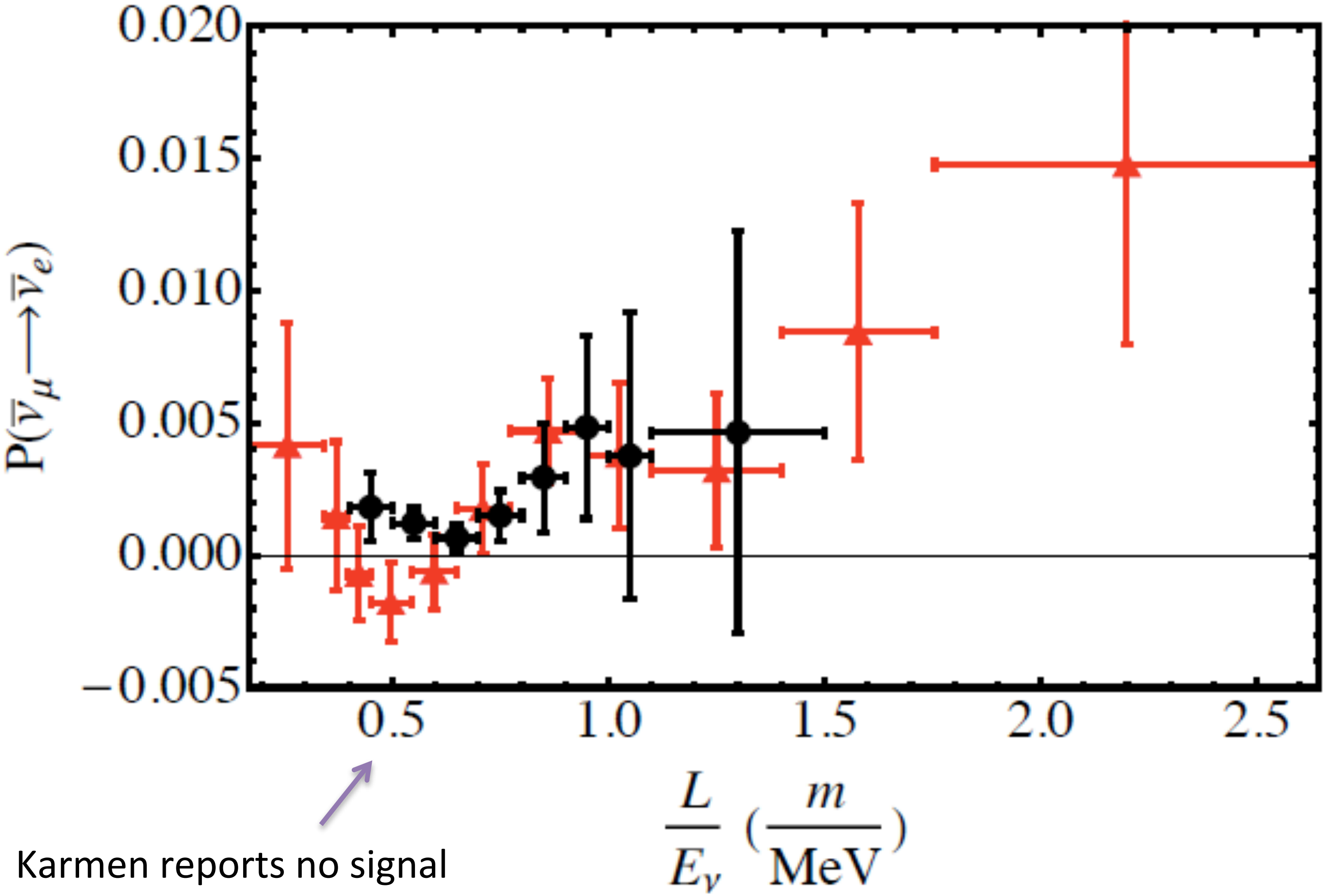


MiniBooNE Results





L/E Comparison of LSND & MiniBooNE Antineutrino mode



Karmen reports no signal around L/E ~ 0.5

Existing Anomalies in Neutrino Physics @ SBL

❖ Experimental anomalies ranging in significance (2.8–3.8σ) have been reported from a variety of experiments studying neutrinos over baselines less than 1 km.

<u>Current anomalies from:</u>
accelerator beams
radioactive sources
reactor neutrinos

Experiment	Type	Channel	Significance
LSND	DAR	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	3.8σ
MiniBooNE	SBL accelerator	$\nu_\mu \to \nu_e$ CC	3.4σ
MiniBooNE	SBL accelerator	$\bar{\nu}_\mu \to \bar{\nu}_e$ CC	2.8σ
GALLEX/SAGE	Source - e capture	ν_e disappearance	2.8σ
Reactors	Beta-decay	$\bar{\nu}_e$ disappearance	3.0σ

K. N. Abazajian et al. "Light Sterile Neutrinos: A Whitepaper", arXiv:1204.5379 [hep-ph], (2012)

❖ Most common interpretation is as evidence for high mass-squared neutrino oscillations and the existence of one or more additional, mostly <u>"sterile" neutrino</u> states with <u>masses at or below a few electron volts</u>

– Many global fits to data (both with signal and null results) available in the literature that fit the data to 3+1, 3+2 and 3+3 models for sterile neutrinos (Kopp et al. Conrad et al., Giunti et al. etc)

❖ While each of these measurements taken separately lack the significance to claim a discovery, together these signals could be hinting at important new physics that requires further exploration

What are the Prospects for Clarifying this Picture and Detecting (or ruling out) Light Sterile Neutrinos?

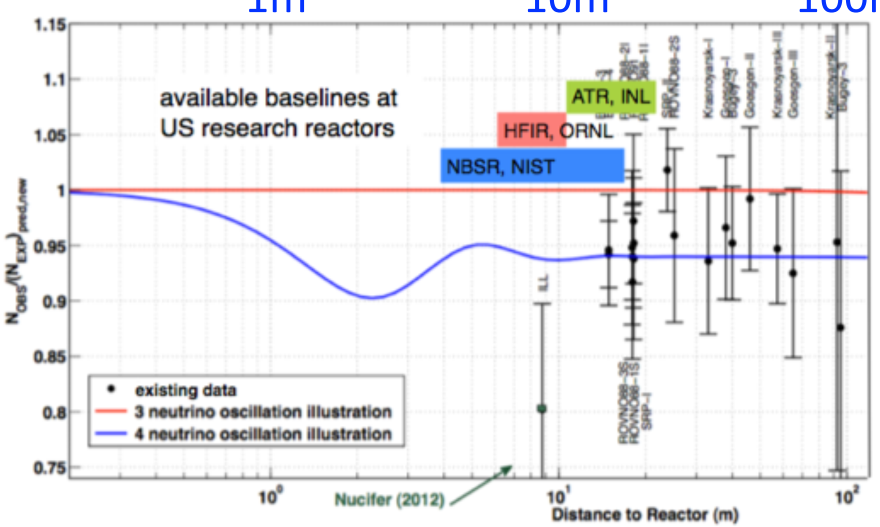
Pursuing Different Approaches May Be Key

"Given the potential implications [and challenges] of sterile neutrinos, it is important to confirm their existence in multiple (preferably orthogonal) approaches." Light Sterile Neutrinos: A White Paper (arXiv:1204.5379)

Radioactive neutrino sources	$\nu_e/\bar{\nu}_e$ dis.	$100s$ of keV, $10s$ of cm
Nuclear reactor antineutrinos	$\bar{\nu}_e$ dis.	< 10 MeV, < 20 m
Stopped π beams	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	~ 30 MeV, 30 m
Stopped K beams	$\nu_\mu \rightarrow \nu_e$	235.5 MeV, 160 m
Decay in flight π/K beams	$\nu_\mu \rightarrow \nu_e$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\nu_\mu/\bar{\nu}_\mu$ dis. , $\nu_e/\bar{\nu}_e$ dis.	500 MeV $-$ 2 GeV 100 m $-$ 2000 m
Atmospheric neutrinos	$\nu_\mu/\bar{\nu}_\mu$ dis.	< 20 GeV, $15 - 130$ km 100 GeV $-$ 400 TeV, $< 1.3 \times 10^4$ km
Cosmology	indirect N_s, m_ν	

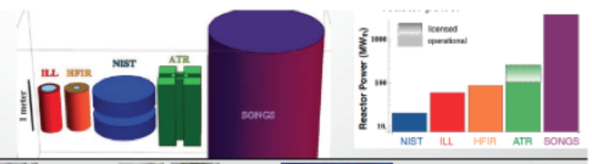
Reactor Neutrino Experiments

- Numerous proposals: Nucifer, Stereo, PROSPECT, SCRAMM,…
- Reactor sites in U.S., Europe, China
- Primary motivation for some experiments (Nucifer, for example) is nuclear reactor monitoring and non-proliferation - compact detector with “simple” technology, remote operations
- Baselines range from 4-30m from reactor core



Potential huge payoff for relatively modest cost experiments (order $5M)

Potential U.S. Reactor sites



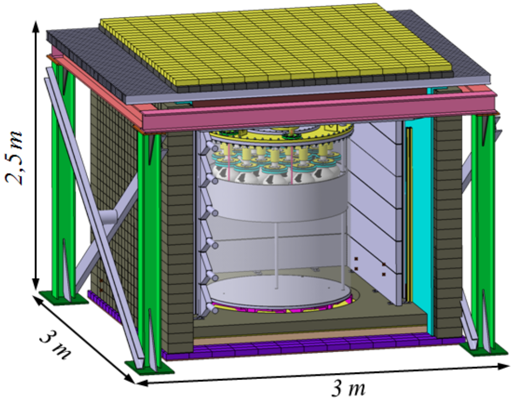
Reactor	NBR NIST	HFIR ORNL	ATR INL	SONGS
Power (MW_{th})	20	85	150	3400
Core Size	Ø100cm x100cm	Ø60cm x100cm	Ø110cm x110cm	Ø3m x 3.8m
Operating Cycle	~1/3 reactor off	~1/3 reactor off	~1/3 reactor off	Currently offline, limited cycle likely
Potential Deployment Sites	4-13m baseline Above-grade, minimal overburden	6-8m baseline Above-grade, minimal overburden	12-20m baseline Below-grade, minimal overburden	24 baseline, 25 m.w.e overburden
Reactor γ/n Background	Measurements underway	Measurements planned	Measurements planned	Negligible

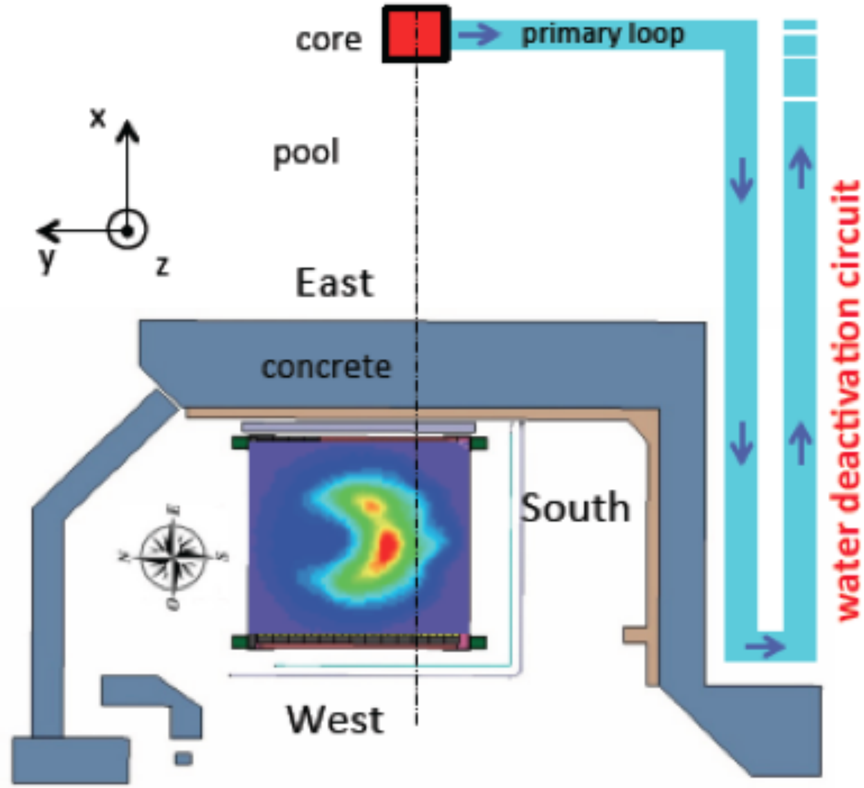
From N. Bowden

Backgrounds Present a Huge Challenge

Huge unexpected reactor-on background from water deactivation circuit. Lesson for future experiments:
It is critical to measure and understand backgrounds at detector site.

Nucifer

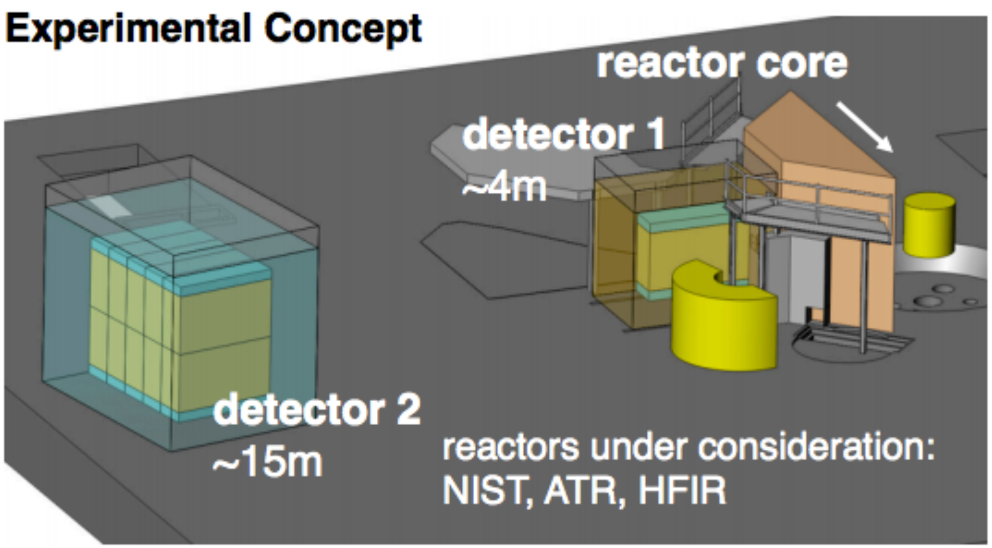


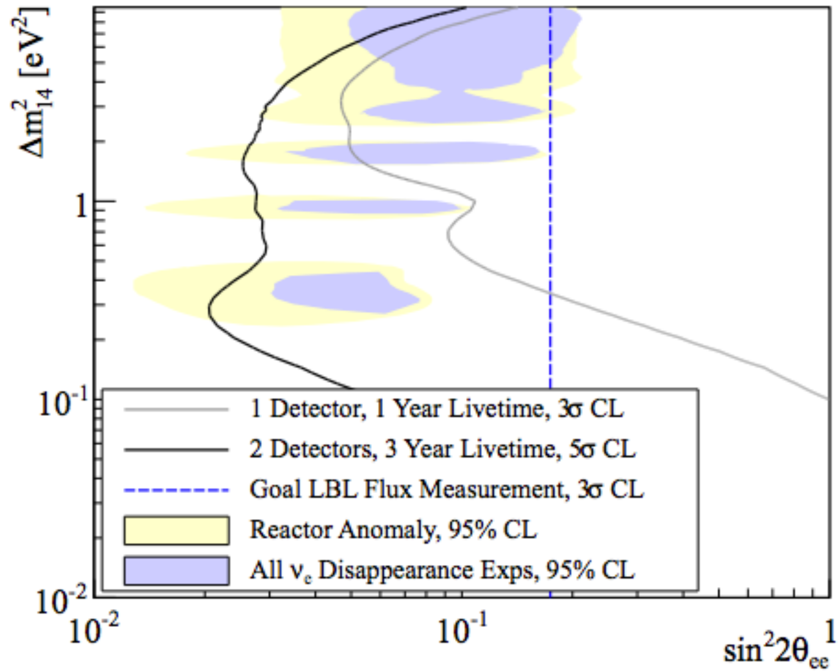


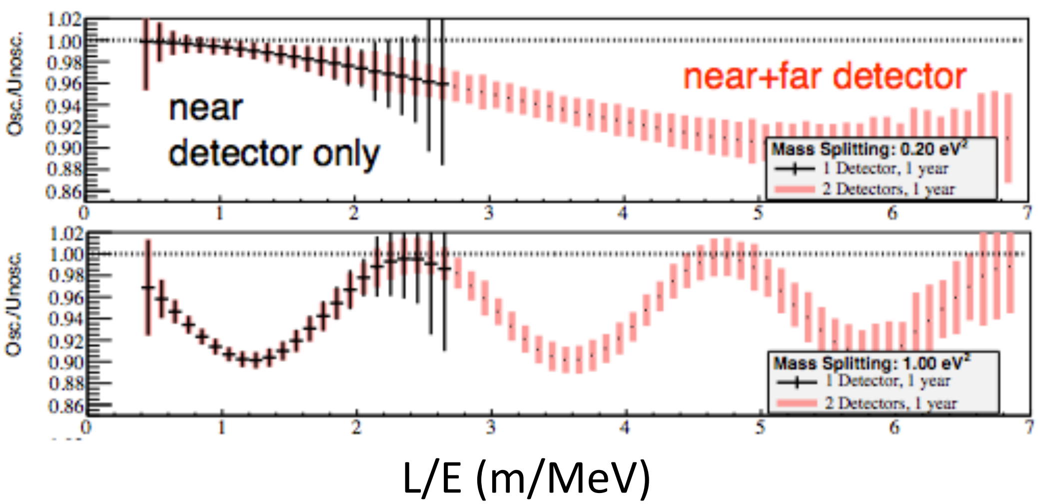
Barycenters of the PMT's charges

The PROSPECT Experiment

Precision Reactor Oscillation and Spectrum Experiment at Very Short Baselines



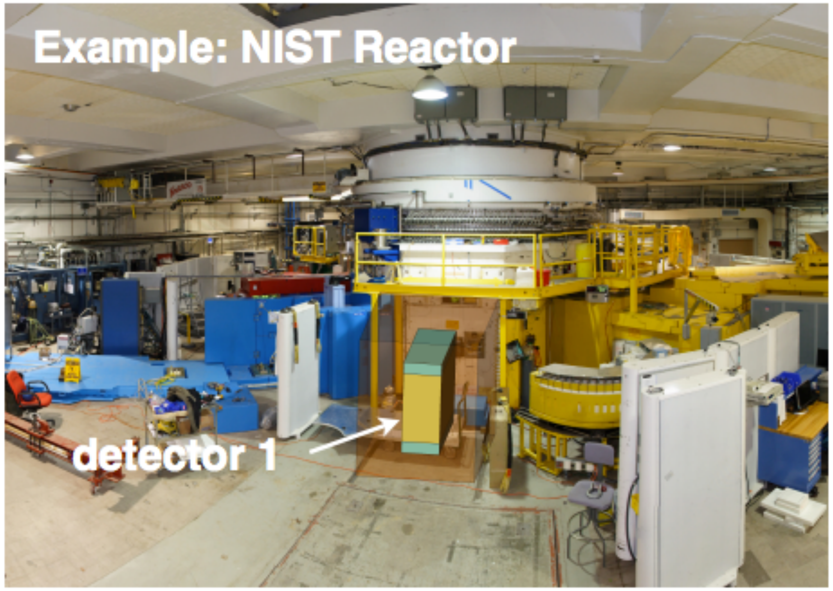


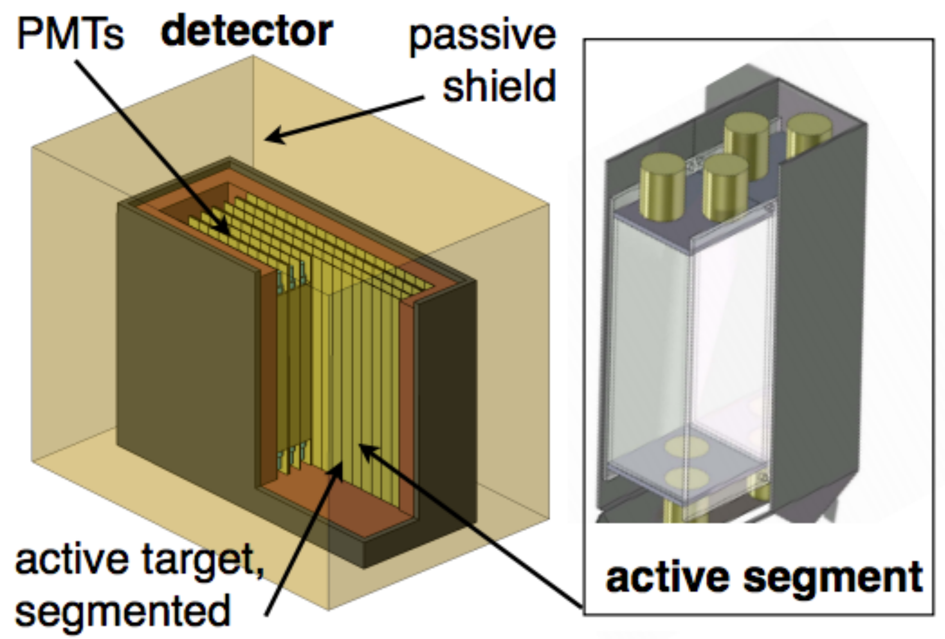


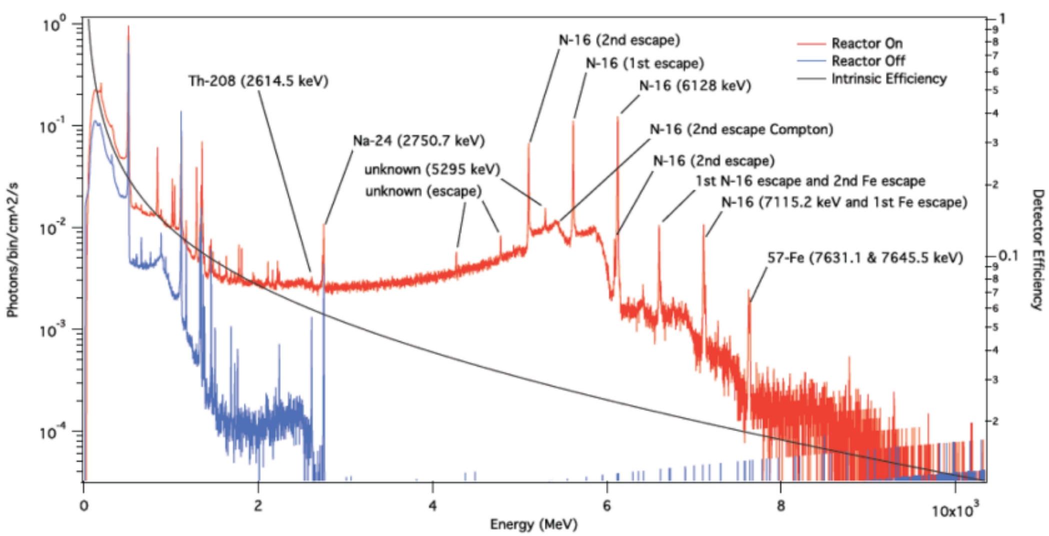
Smoking-gun oscillation pattern

J. Ashenfelter et al., arXiv:1309.7647

The PROSPECT Experiment







On-going effort to understand backgrounds (both reactor-off and reactor-on) in proposed detector locations

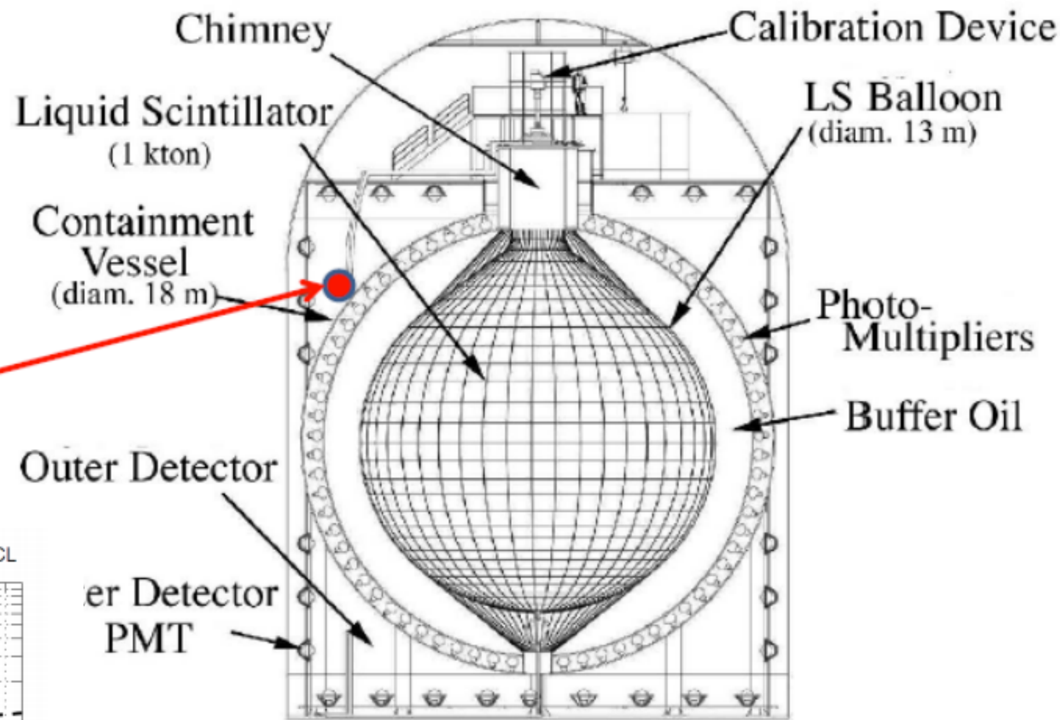
J. Ashenfelter et al., arXiv:1309.7647

Radioactive Source Experiments

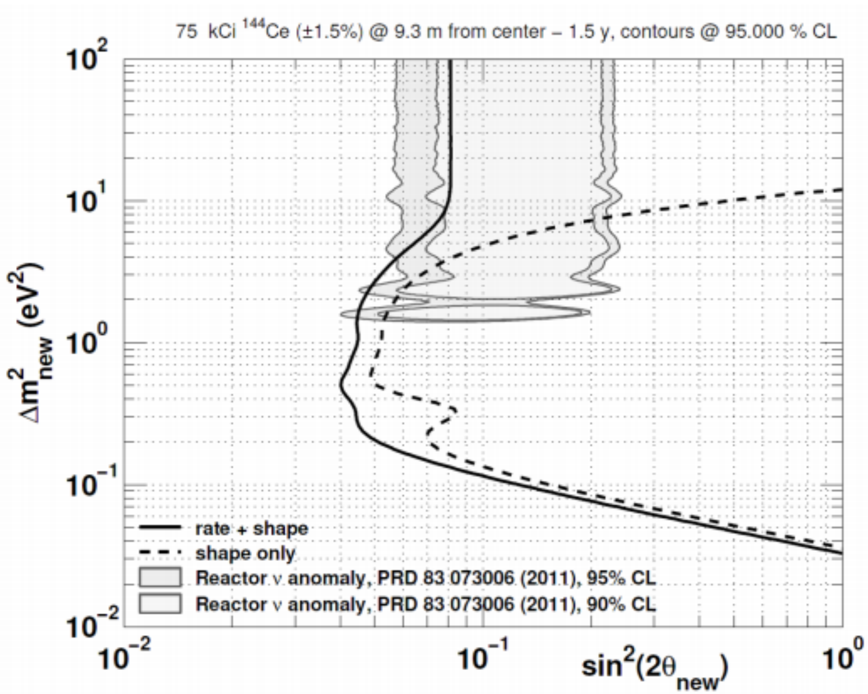
- Another potentially fast and relatively inexpensive way to pursue sterile neutrino oscillations
- Largely because these experiments use existing neutrino detectors
- Both neutrino sources ^{51}Cr (chromium) and antineutrino sources ^{144}Ce-^{144}Pr (cerium-praseodymium) are being considered

CeLAND Source Experiment

Place an antineutrino source in outer detector region of KamLAND



A. Gando et al., arXiv:1309.6805



95% contours shown for 1.5 years of data

Sensitivity at high Δm^2 depends on knowing absolute intensity of source

Source Experiment at Borexino (SOX)

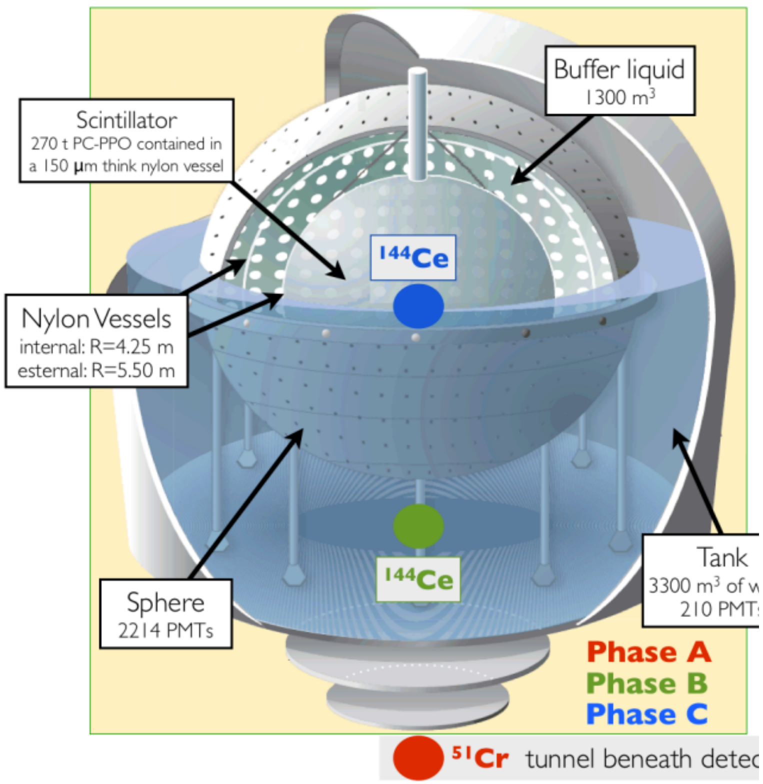
G. Bellini et al., arXiv:1304.7721

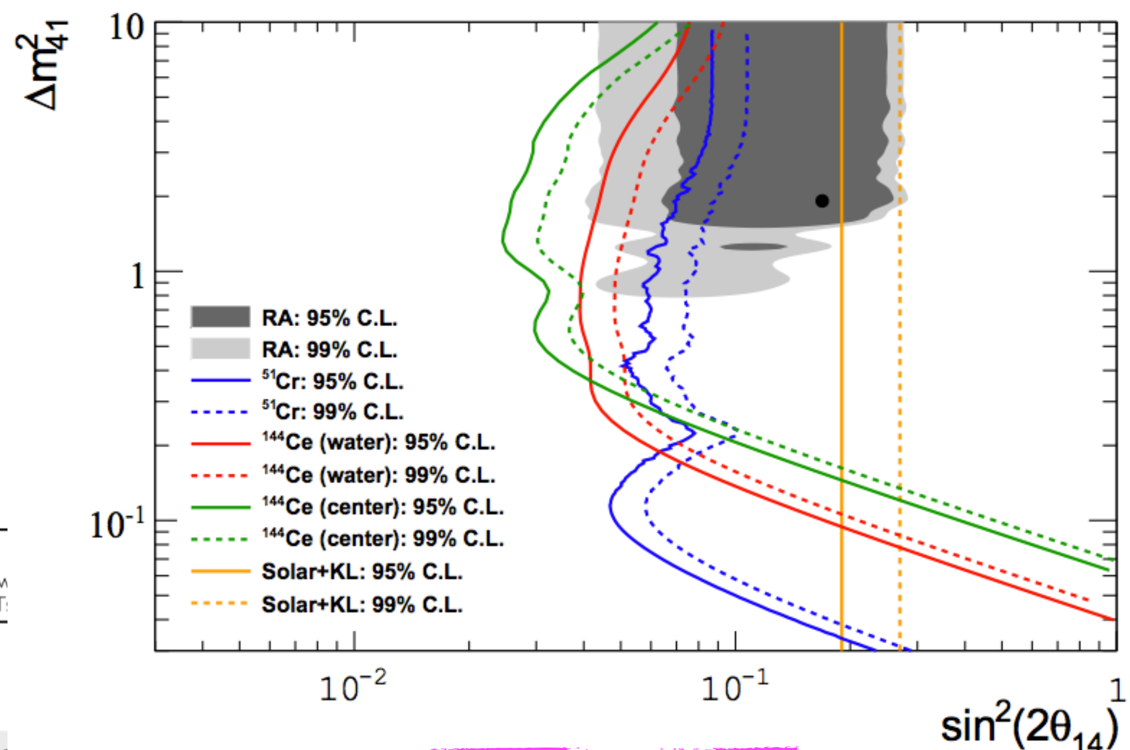
- Use well known neutrino ^{51}Cr source
- Or antineutrino ^{144}Ce-^{144}Pr source
- With a well understood detector

^{51}Cr neutrinos: $E_\nu = 750$ keV

^{7}Be neutrinos: $E_\nu = 787$ keV

liquid scintillator detector

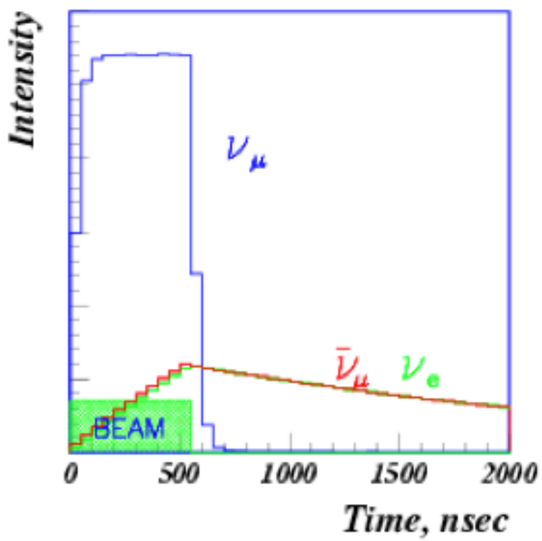


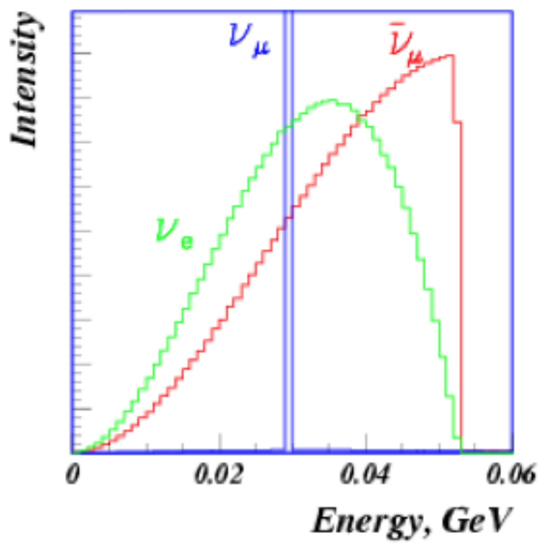


Location matters

Decay-At-Rest Source Experiments

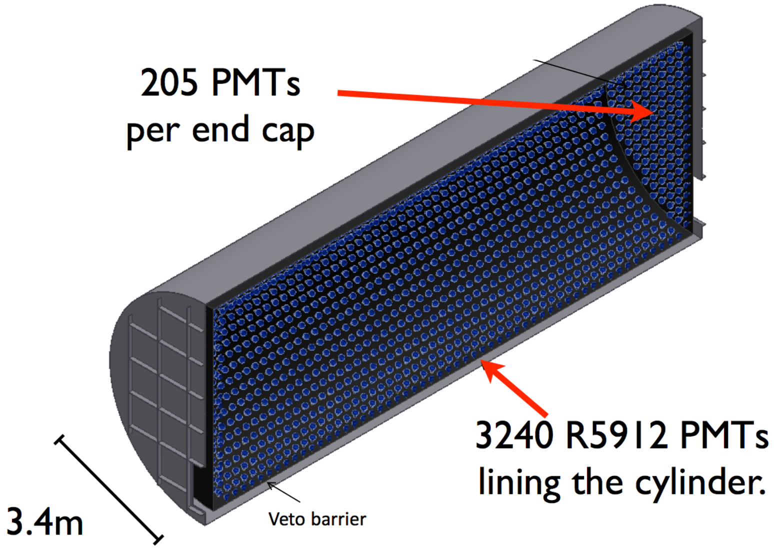
- Decay-At-Rest sources provide large, well-understood neutrino fluxes
- High-statistics could allow experiments to observe the characteristic L/E shape across a detector
- π Decay-At-Rest
  - OscSNS experiment
- K Decay-At-Rest
- Isotope Decay-At-Rest
  - IsoDAR experiment





The OscSNS Experiment

- Make use of the “free” neutrino source at the Spallation Neutrino Source (SNS) at Oak Ridge NL
- $2\text{x}10^{23}$ protons on target per year
- Build a neutrino detector near the source

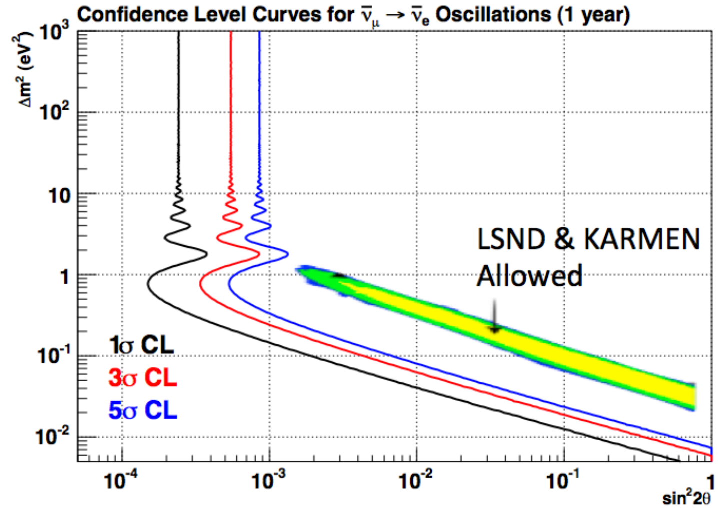


The OscSNS Experiment

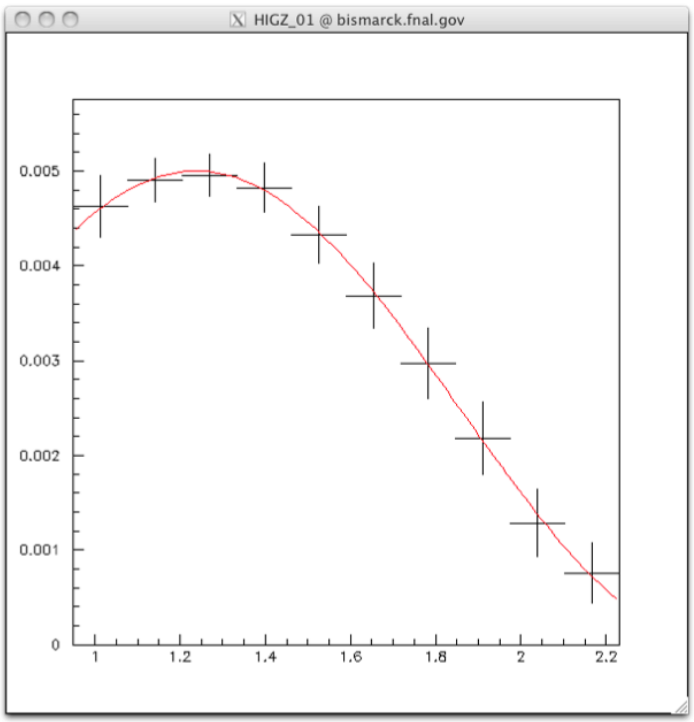
- Compared to LSND
  - Mass 5x larger
  - Neutrino source intensity 2x greater
  - Duty factor 1000x smaller (less cosmogenic background)
  - Negligible decay in flight by putting detector behind the proton target
  - Separation of ν_μ and $\nu_e/\bar{\nu}_\mu$ by timing
  - Expect 350 $\bar{\nu}_e$ oscillation events per year with 80 background events

The OscSNS Experiment

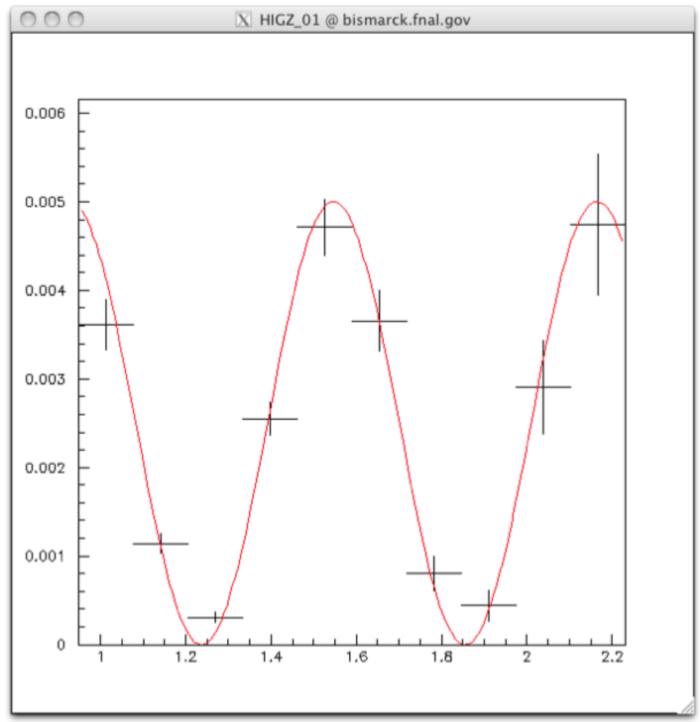
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$



Assuming 10y of data & $\sin^2 2\theta = 0.005$, $\boxed{\Delta m^2 = 1\ eV^2}$



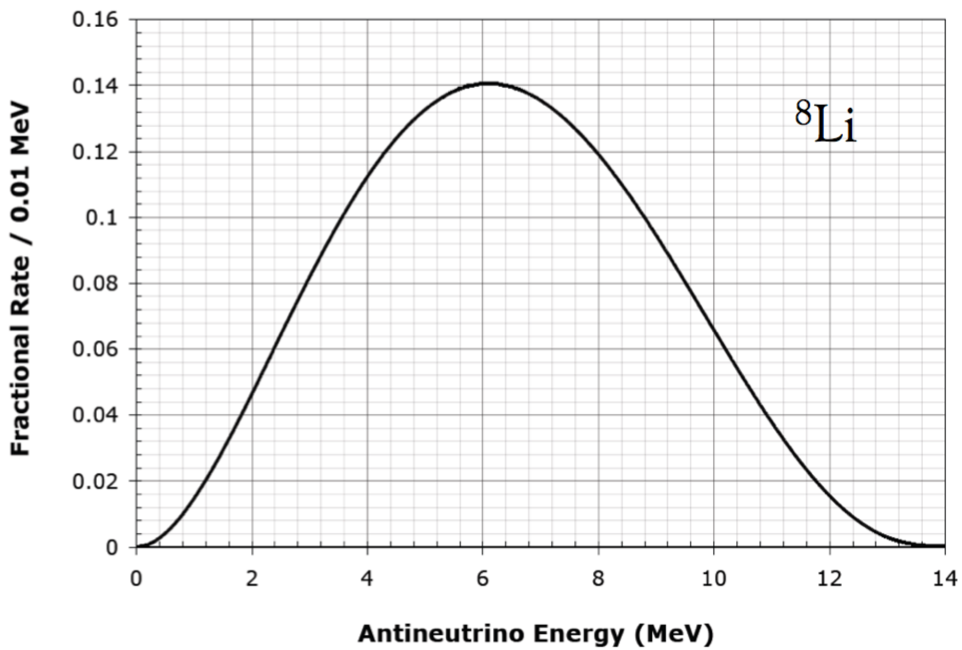
Assuming 10y of data & $\sin^2 2\theta = 0.005$, $\boxed{\Delta m^2 = 4\ eV^2}$



L/E (m/MeV)

The IsoDAR Experiment

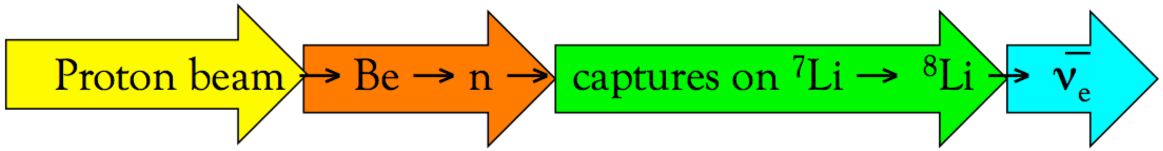
- The beta-decay-at-rest of ^{8}Li isotope produces $\bar{\nu}_e$ above 3 MeV
- But need to make a lot of ^{8}Li close to an underground detector that can see inverse beta decay

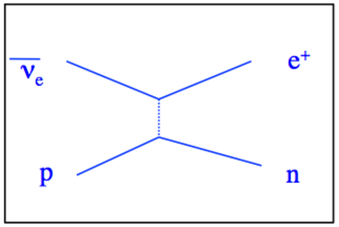


But only a few isotopes have endpoints > 3 MeV, above environmental backgrounds that affect detectors.

e.g.
$^8\text{Li} \rightarrow {}^8\text{Be} + e + \bar{\nu}_e$

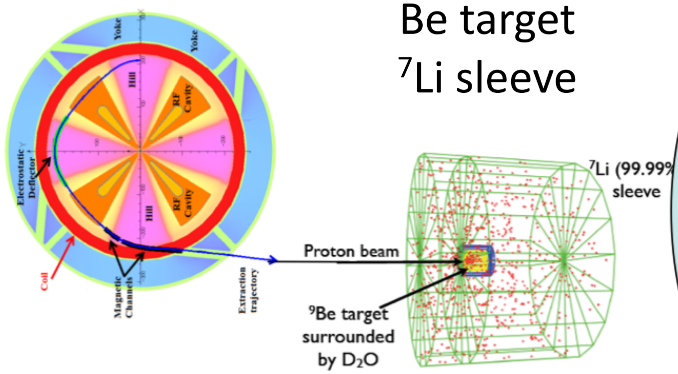
The IsoDAR Experiment

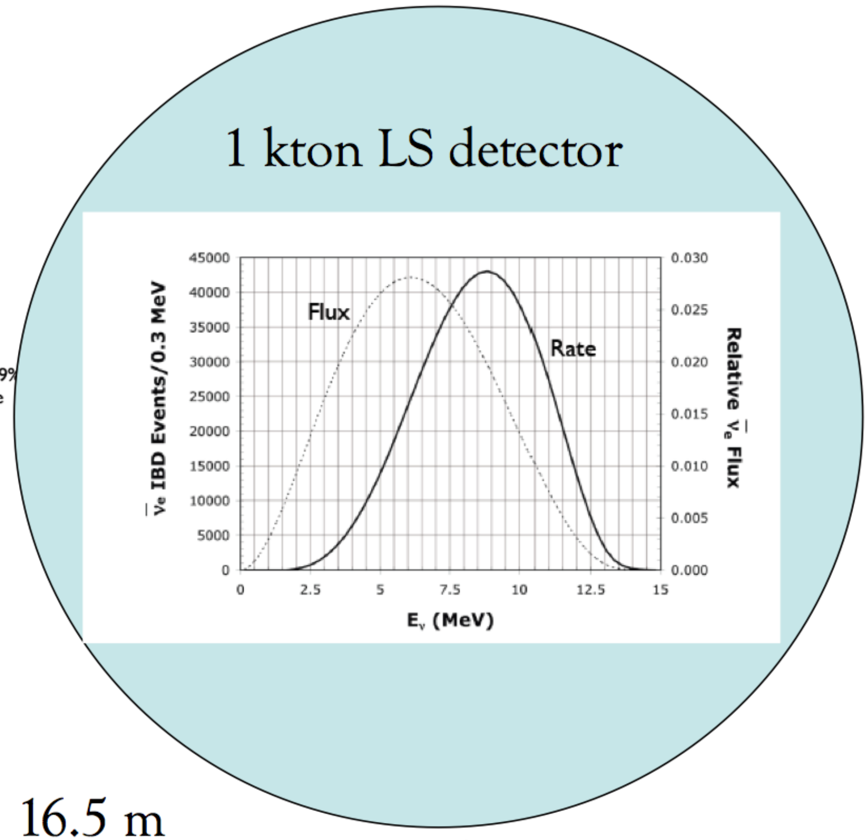




cyclotron driver

Be target
^{7}Li sleeve

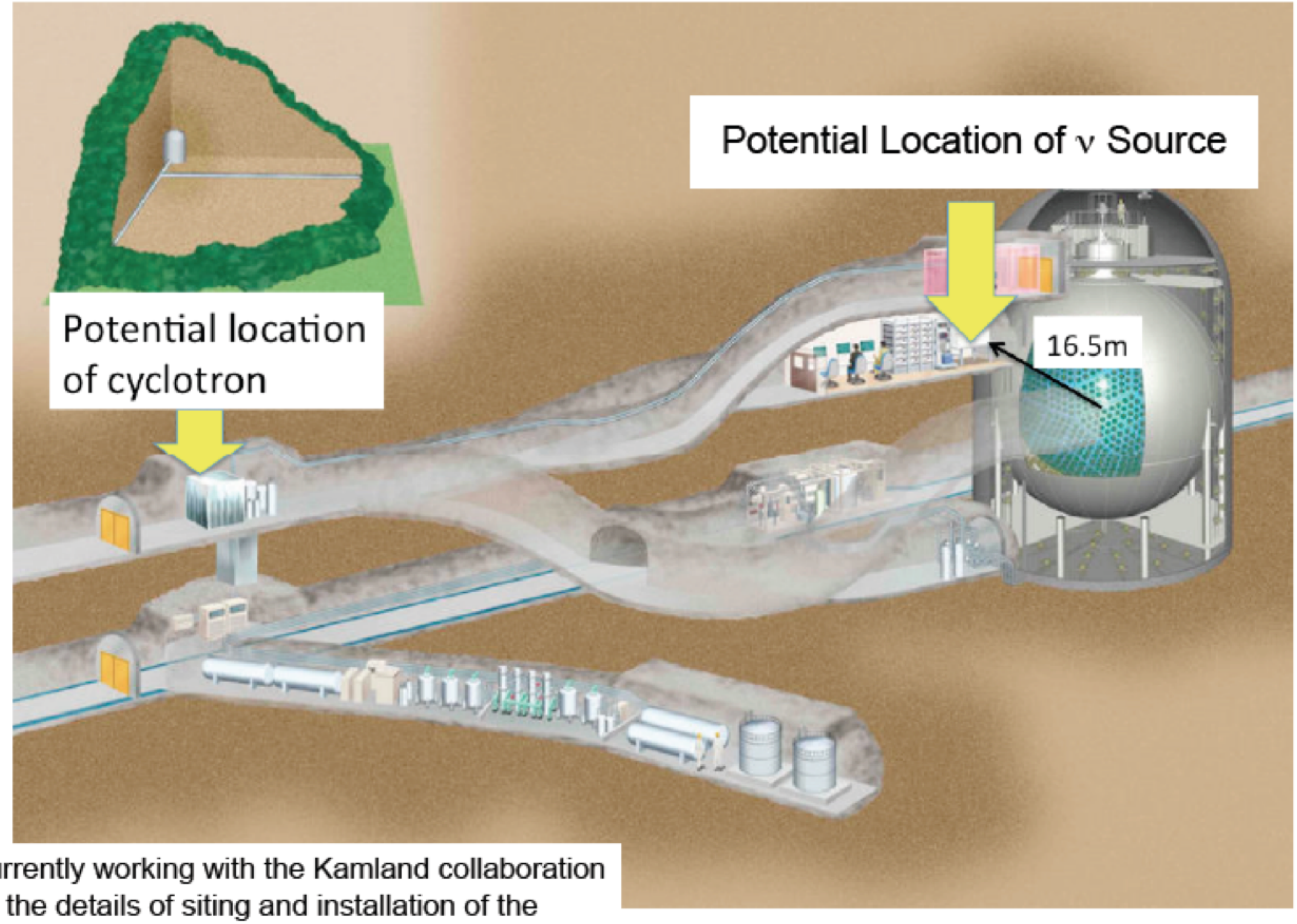




16.5 m

The IsoDAR Experiment

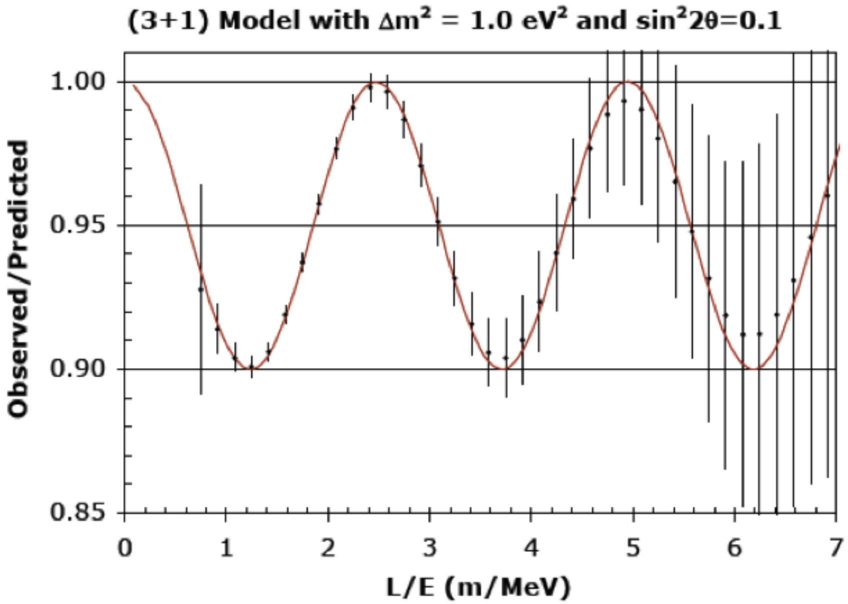
KamLAND would work perfect



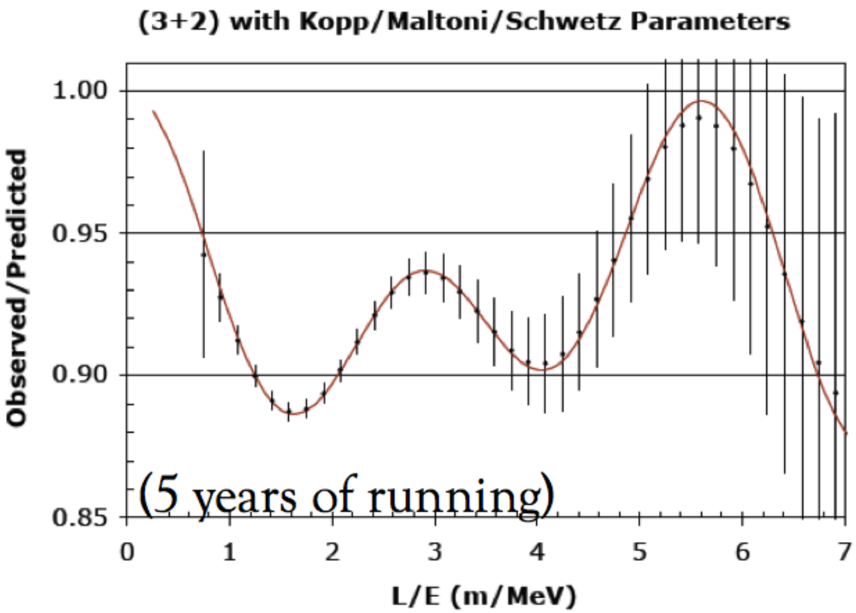
Currently working with the Kamland collaboration on the details of siting and installation of the cyclotron, beamline, and neutrino source.

The IsoDAR Experiment

3+1

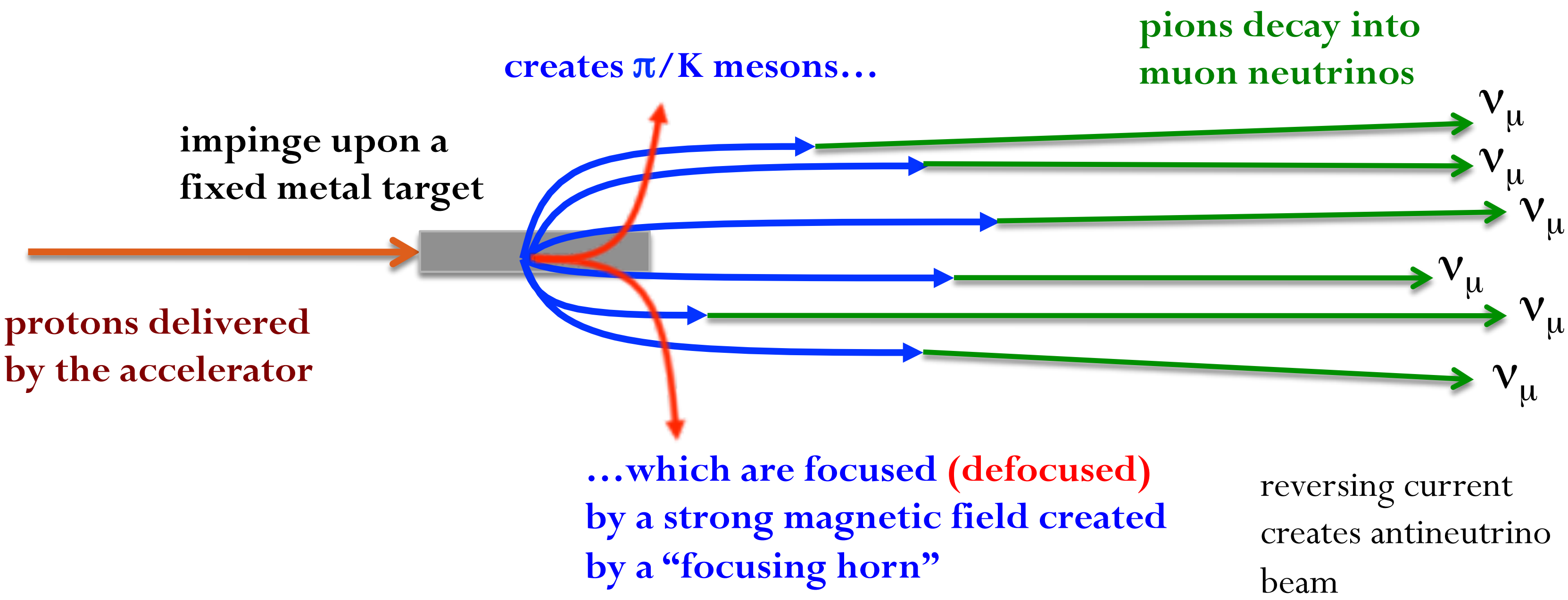


3+2



Possibility to distinguish between 1 and multiple sterile neutrino models through oscillation pattern!

π Decay-In-Flight Experiments



Relevant features of all DIF ν beams:

1. $\nu_\mu(\bar{\nu}_\mu)$ flavor beam to first order
2. always some (order 1%) $\nu_e(\bar{\nu}_e)$
3. "wrong sign" content not negligible (especially in antineutrino mode)
4. on-axis beam will span ν energies, mean increases some with proton energy
5. notoriously difficult to know fluxes with high precision

π Decay-In-Flight Experiments

DIF beam provides a rich oscillations program with a single facility:

- $\nu_\mu \rightarrow \nu_e$ appearance
- ν_μ and ν_e disappearance
- both neutrinos and antineutrinos
- CC and NC interactions

Anomalies exist here (MiniBooNE neutrino and antineutrino) and these need to be addressed

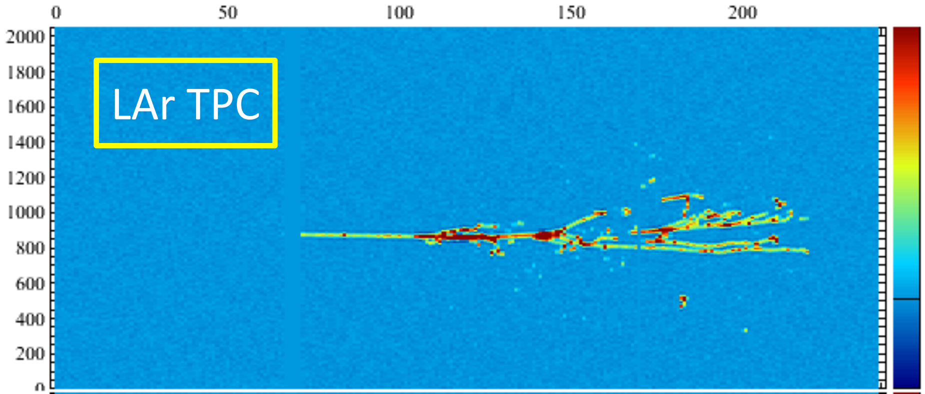
Need detectors that can distinguish electrons from photons

Multiple detectors very valuable for reducing systematic uncertainties

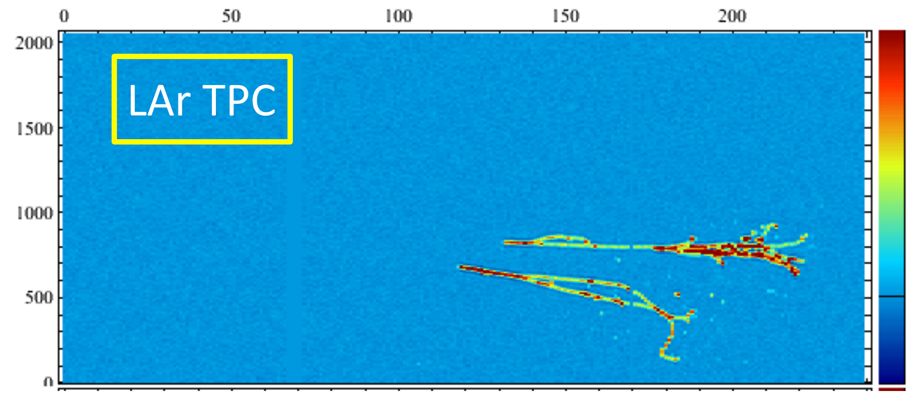
Fermilab is taking the next step on this front with the MicroBooNE experiment

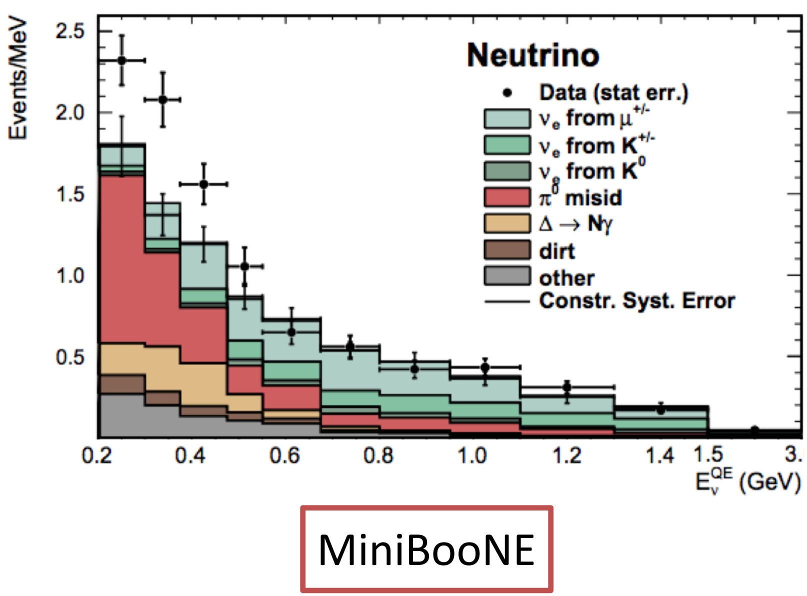
Electron/photon Separation with LAr TPCs

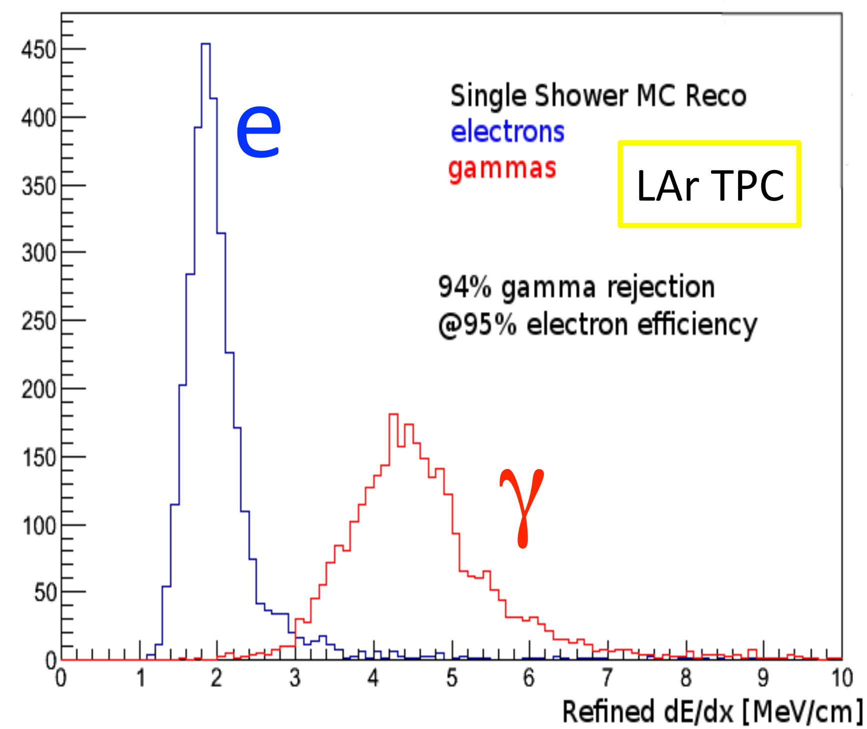
1 GeV electron shower



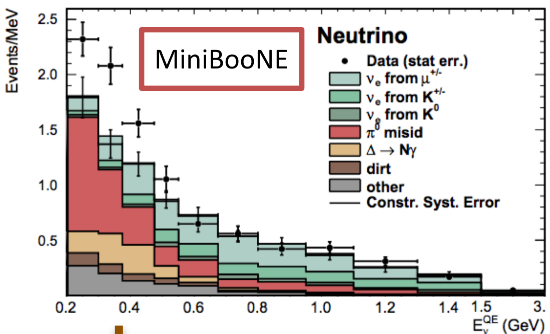
Decay of a 1 GeV π^0 to two photons.

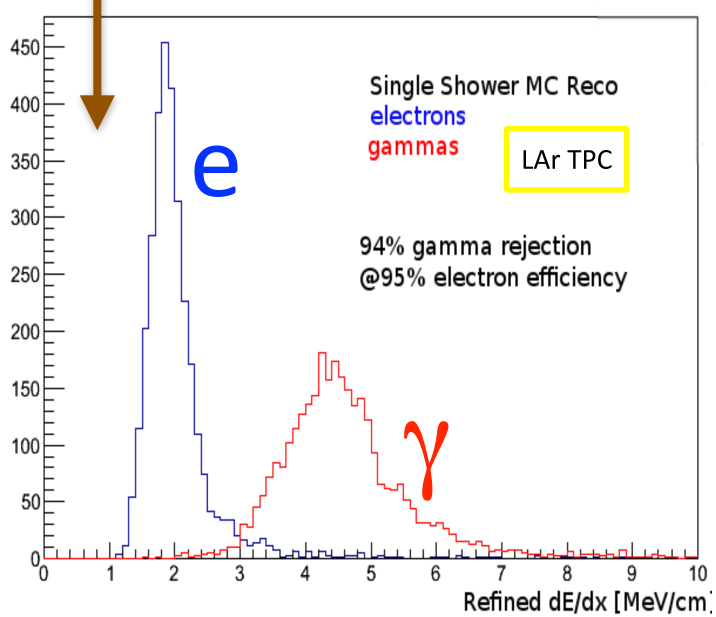






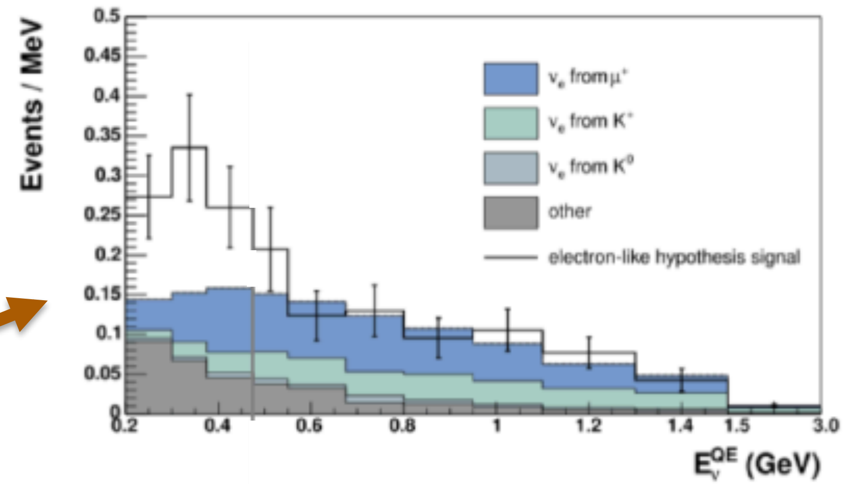
MicroBooNE @ ~500m





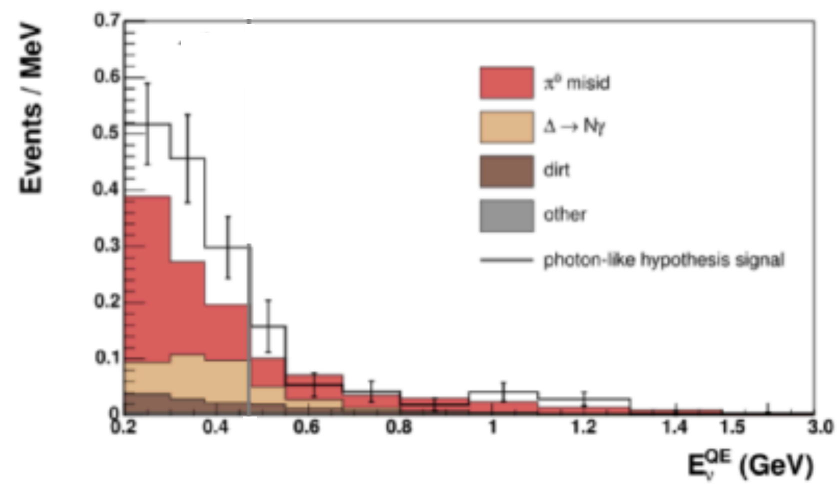
electrons

$>5\sigma$ stat. significance if all electrons



photons

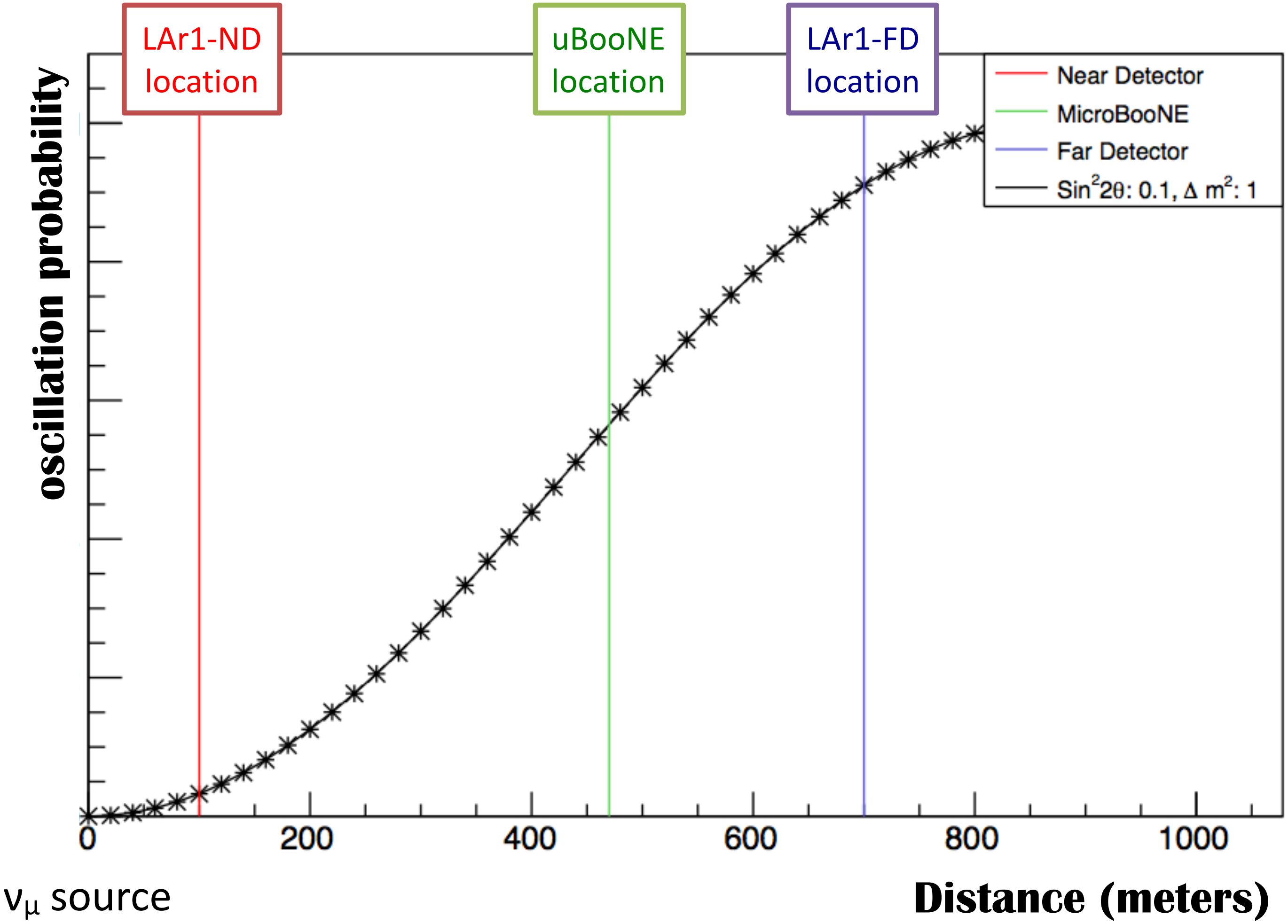
$>4\sigma$ stat. significance if all photons



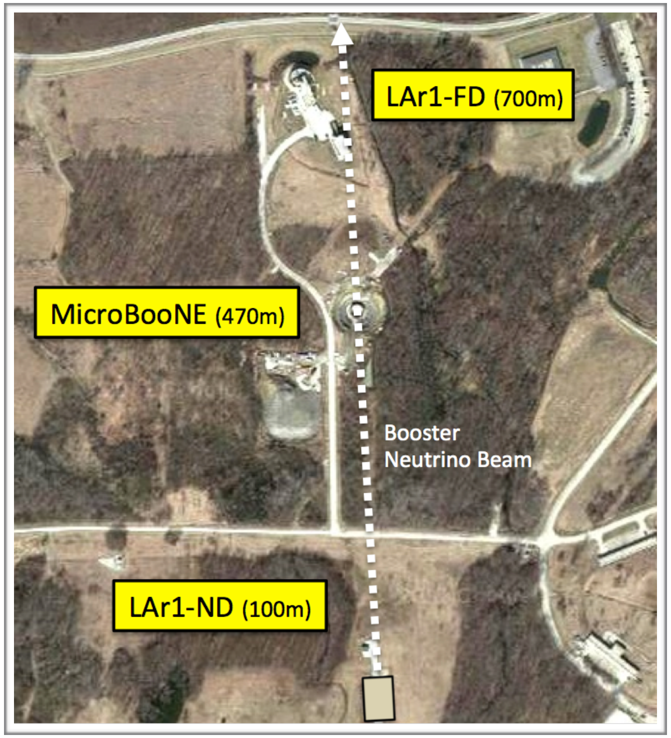
MicroBooNE can investigate a critical piece of the puzzle: **are the excess events seen by MiniBooNE <u>electrons</u> or <u>photons</u>?**

Fermilab Short-Baseline Neutrino Program

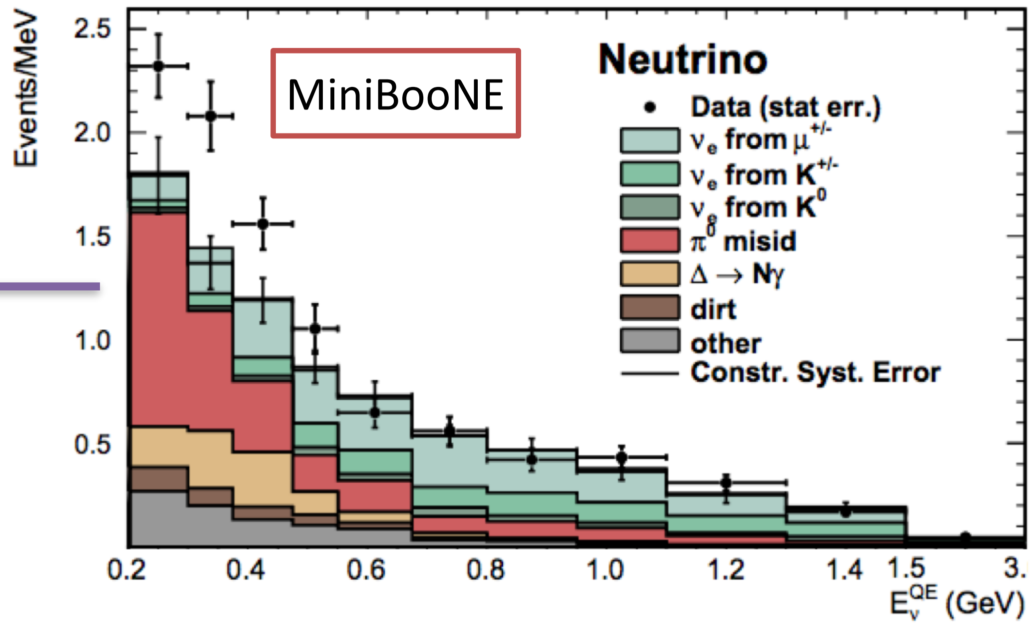
ν_μ disappearance probability at $\mathbf{E_\nu}$ = 700 MeV as a function of distance in a sterile neutrino model with $\Delta \mathbf{m^2 = 1.0\ eV^2}$



Length Dependence of Excess



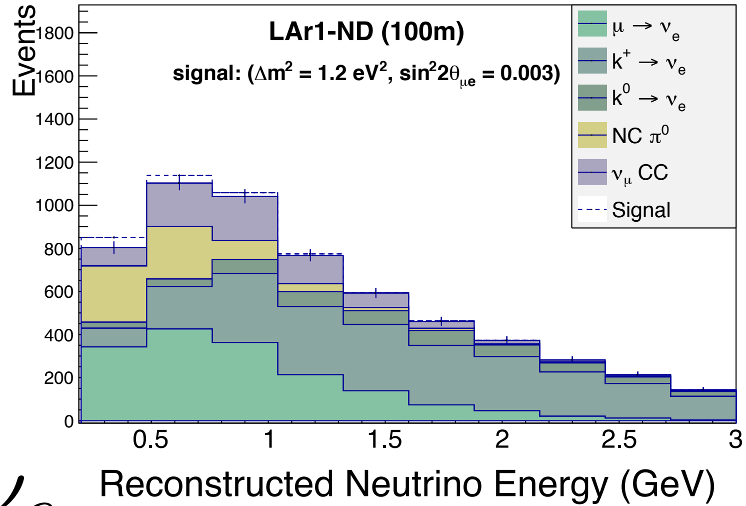
A. A. Aguilar-Arevalo *et al.*, Phys. Rev. Lett. 110 161801 (2013)

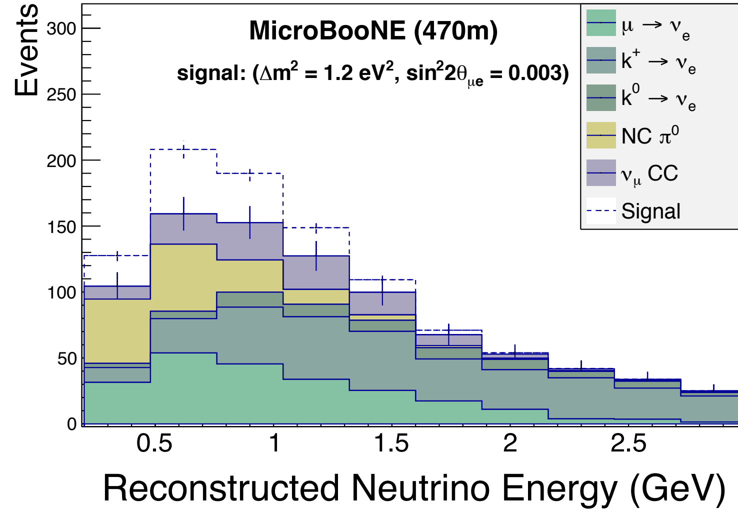


By scaling directly from observed rates in MiniBooNE, MicroBooNE expects to see ~50 background and 50 excess events in 6.6x10^{20} POT run

Assuming NO L/E dependence LAr1-ND would expect to see ~320 background and 300 excess events in 2.2x10^{20} POT run

$\nu_\mu \rightarrow \nu_e$ Appearance

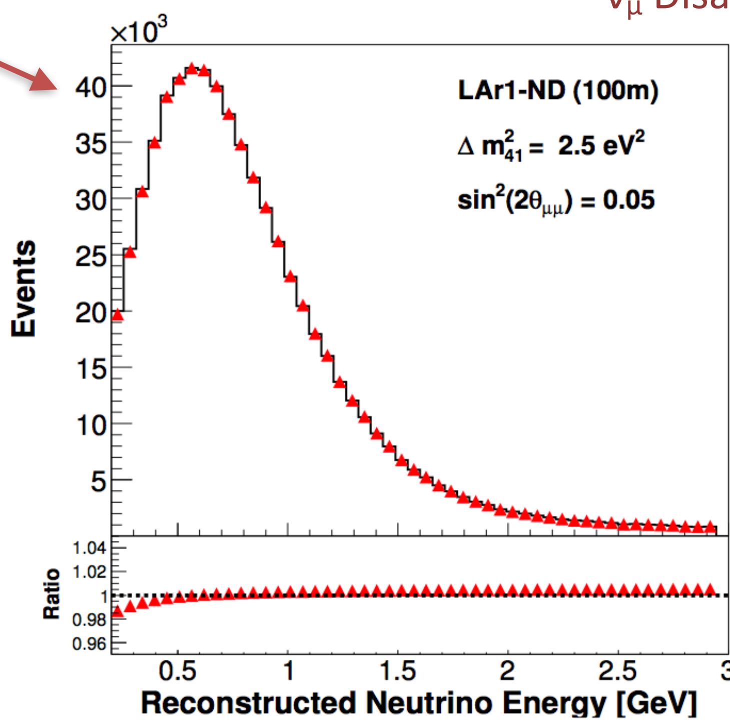


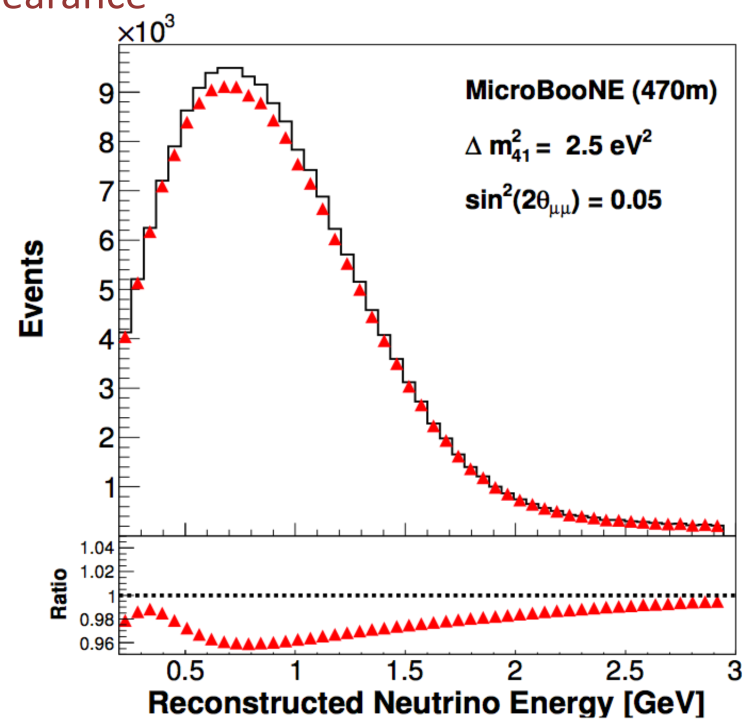


ν_e

$\nu_\mu \rightarrow \nu_s$

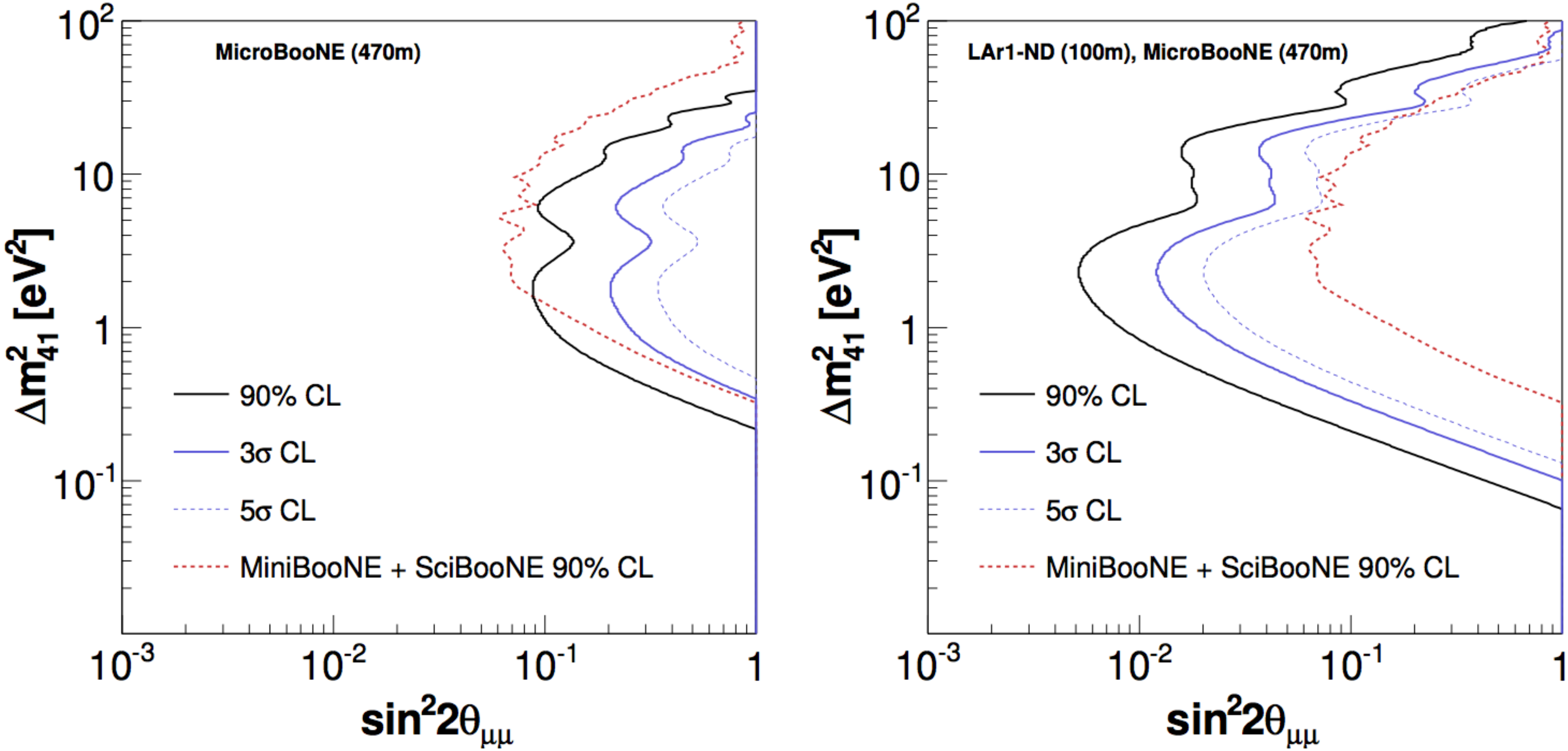
ν_μ Disappearance





❖ Testing ν_μ disappearance only enabled with near detector constraint

❖ Flux and cross section errors of 15-20% conceal a disappearance signal in MicroBooNE alone, but using an observed LAr1-ND spectrum to normalize the expected rate at MicroBooNE makes it observable

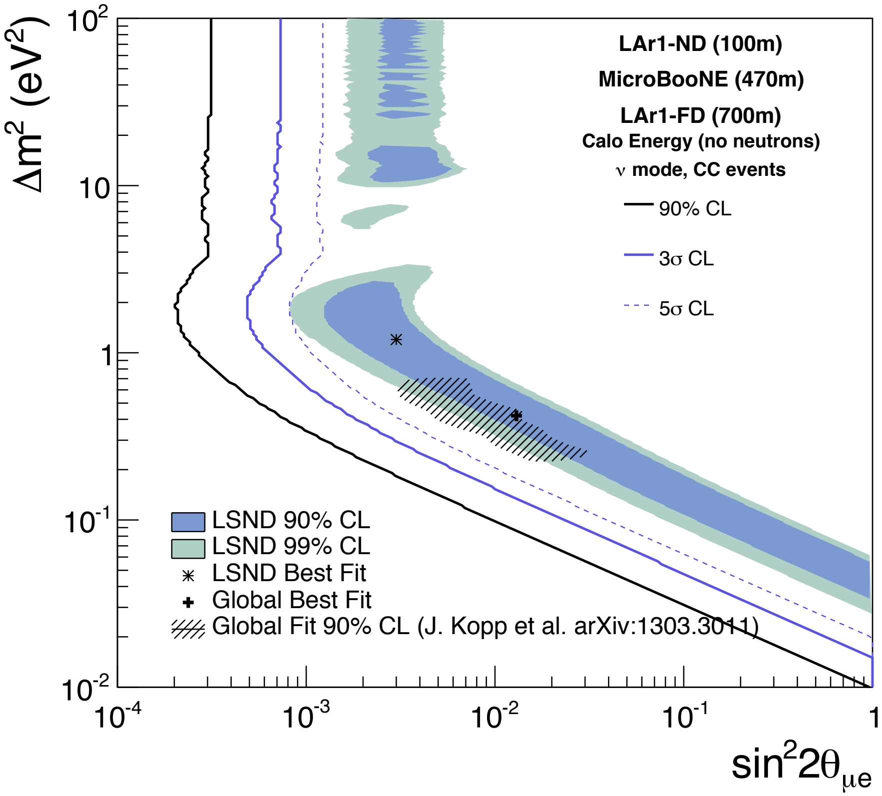


❖ Previous result from MiniBooNE+SciBooNE (red dashed contour) - unlike here, detectors were different technologies, and detector related uncertainties did NOT cancel

The Full LAr1 Short-Baseline Neutrino Program

- The addition of a large (kiloton-scale) detector at longer baseline (~700 m) could address oscillations in anti-neutrino mode and make precision measurements of sterile neutrino oscillations if they are discovered

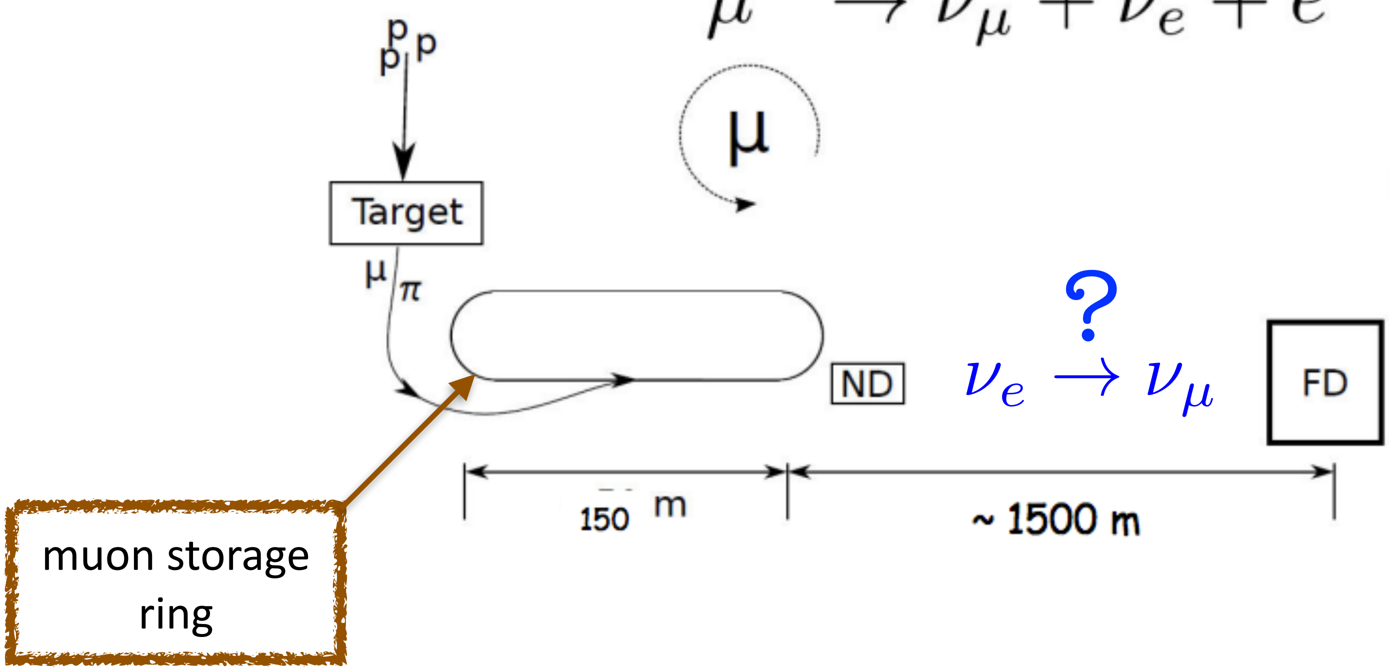
- Three detector configuration provides a powerful confirmation of the interpretation of any results as an oscillation signal



NuSTORM

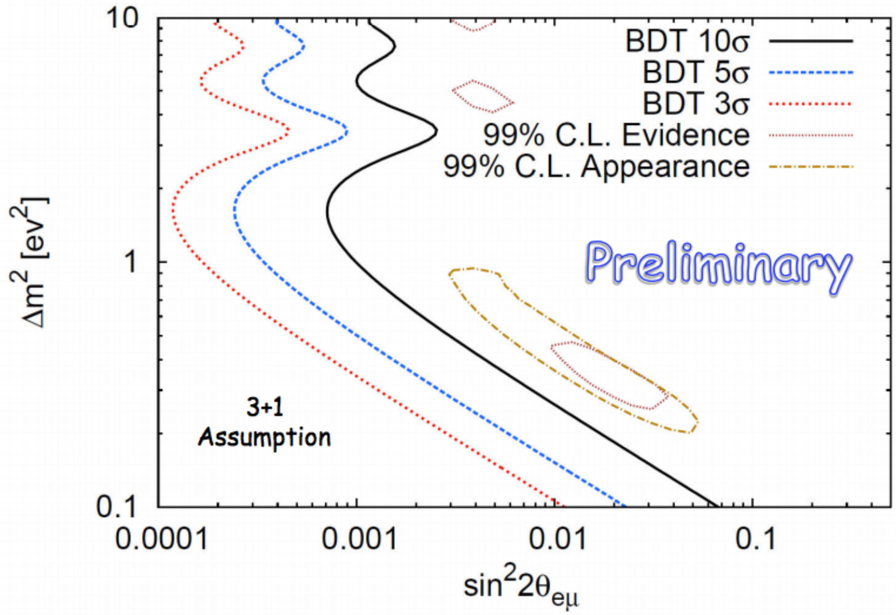
- Muon storage ring, decay-in-flight produces very well understood neutrino beam of ν_e and $\bar{\nu}_\mu$
- Look for oscillations through $\nu_e \rightarrow \nu_\mu$ appearance!
- Best sensitivity going for 3+1 sterile model due to huge rate and low backgrounds for muon neutrino appearance

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$



NuSTORM

$$\nu_e \rightarrow \nu_\mu$$



Summary

- Do sterile neutrinos exist? I don't know!
- But this is a place where neutrino physics is currently confronting potentially new physics, searching for a new class of fundamental particles.
- This challenging question will require a range of complimentary experimental approaches to figure out.
- We will follow the data and see where it leads us!